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Fish Passage Mortality in a Tube Turbine

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FOREWORD

This research resulted from an unsolicited proposal by Monenco Maritimes Limited, to the Canadian Department of Supply and Services. The study was conducted on behalf of the Canadian Department of Energy, Mines and Resources under the direction of Mr. Tony Tung, Renewable Energy Division. The support of Canada Fisheries and Oceans, the Nova Scotia Power Corporation and the Nova Scotia Department of Fisheries is gratefully acknowledged. Mr. N.H Collins provided assistance supervising the field testing portion of the study and supplied computer and statistical advice during data analysis.

ABSTRACT

Ruggles, C.P. and T.H. Palmeter. 1989. Fish passage mortality in a tube turbine. Can. Tech. Rep. Fish. Aquat. Sci. No. 1664.

Fish passage tests in a tube-type turbine located on the Sissiboo River, Nova Scotia were conducted using juvenile trout, alewife and yellow perch. The average turbine related mortality was estimated to be 18% to 25% for trout, 14% for alewife and 13.6% for yellow perch. Water temperature was the most significant variable influencing fish mortality during passage through the turbine. Data are presented which indicate that previous estimates of juvenile alewife mortality due to turbine passage at other hydroelectric sites may be too high. The manner in which fish mortality estimates were derived had a profound impact on the results of fish passage research at this 3.1 MW tube turbine.

Résumé

On réalisé des études sur le passage du poisson (en 1'occurrence, truites juvéniles, gaspareau et perche) dans une turbine de type tubulaire située sur la rivière Sissiboo (Nouvelle-Écosse). Les estimations de mortalité moyenne due a la turbine étaient de l'ordre de 18% a 25% pour la truite, de 14% pour le gaspareau et de 13,6% pour la perche. La température de 1'eau a été la variable qui a eu le plus d'influence sur la mortalité du poisson durant le passage dans la turbine. Les données présentées ici révèlent que les estimations antérieures sur la mortalité des gaspareaux juvéniles due au passage dans des turbines d'autres centrales hydro-électriques apparaissent trop élevées. La facon dont les estimations de mortalité du poisson ont été obtenues a eu un effet déterminant sur les résultats de 1'étude du passage du poisson dans cette turbine de 3,1 MW.

INTRODUCTION

The completion of large hydroelectric projects and the renewed interest in developing small-scale hydropower projects, will result in more water flowing through turbines. Turbine related impacts may be particularly severe to juvenile anadromous fishes during their downstream migration to the sea. In the case of tidal power development, both juvenile and adult migratory species may be vulnerable to turbine induced mortality. Existing information on turbine-related fish mortality is primarily derived from studies undertaken in the Columbia River drainage basin by the Fisheries Research Engineering Program, U.S. Army Corps of Engineers, North Pacific Division and, to a lesser extent, from investigations conducted in western and eastern Canada.

The concern about potential environmental impacts related to small-scale hydro development prompted the American Electric Power Research Institute to sponsor a workshop on fish passage through hydraulic turbines. Experts in the fields of turbine engineering and biologists working on assessing turbine fish passage met to review the subject of safe passage of fish through turbines (Eicher Associates Incorporated, 1985). Two important conclusions arising from this meeting were the need to address the lack of studies of fish passage through bulb and tube type turbines, and the relative lack of information about turbine induced mortality of clupeids (shad, alewives and herring) as compared to salmonids (salmon and trout).

In 1985, testing at the Annapolis River tidal-powered STRAFLO turbine (a very large tube turbine) in Nova Scotia showed a 46.3± 34.7% mortality of adult shad (Hogans and Melvin 1985). Observation of the river bottom at the turbine discharge opening by SCUBA divers in early July revealed large numbers of macerated fishes of several species including alewife, shad and striped bass. The magnitude of the fish passage problems was not foreseen, based on interpreting the results obtained from Francis and Kaplan turbines and research undertaken with salmon and trout. Even small juvenile clupeids (mostly alewife) suffered 54% mortality passing through the STRAFLO turbine (Stokesbury 1986).

Because of the relatively large flows (400 $m^3.s^{-1}$) and the tidal influence, the Annapolis site is not ideal for conducting fish turbine passage tests. Experience has shown that total fish recapture is the most effective experimental design to quickly gather unambiguous results. The technical and practical problems associated with recapturing all test and control fish at Annapolis has seriously impeded obtaining a clear insight into the magnitude and nature of fish passage mortality in the STRAFLO turbine. On the basis of results so far achieved at Annapolis, it is difficult to explain the apparent high fish mortality on the basis of turbine design, fish species, the operating

characteristics associated with tidal power generation, or problems inherent in estimating turbine induced fish mortality.

In order to document fish passage mortality in tube-type turbines, to compare fish mortality of clupeids and salmonids, and to help identify reasons for the unexpected fish mortality at the Annapolis tidal power site, Monenco Maritimes conducted turbine fish passage research at a small tube turbine located on the Sissiboo River, Nova Scotia. The turbine is installed at the outlet of Fourth Lake at a location that provides a practical test site for fish passage research since the flows are only about 11 $m^3.s^{-1}$, allowing for a relatively high rate of recapture of test and control fish. Results obtained at Fourth Lake are interpreted in the light of turbine design and operating characteristics, fish species, experimental design and the types of injuries observed.

Extensive literature reviews on fish passage through turbines are provided by Bell et al. 1967, Ruggles and Collins 1981, Turbak et al. 1981, Bell 1984 and Eicher Associates 1987. These reviews indicate that no fish passage tests have been undertaken on tube-type turbines. In fact, some preliminary testing had been conducted in 1985 and 1986 at the Annapolis River Tidal Power site where a large tube-type turbine is installed. A complete bibliography of all known turbine fish passage research conducted up to 1987 is included in this report.

DESCRIPTIONS OF HYDRAULIC TURBINES

Hydraulic turbines may be broadly classified into two general groups: the tangential or impulse type, which utilizes the kinetic energy of a high-velocity jet acting at atmospheric pressure on relatively small buckets on the circumference of a wheel; and the reaction type, which develops power from the combined action of water pressure and velocity on relatively large submerged blades or buckets incorporated in a turbine runner (Russel 1954). A typical reaction type turbine installation is shown in Figure 1.

Reaction type turbines can be further subdivided into the Francis type, in which water enters the outer periphery of the runner and moves toward the shaft at right angles to it, changing direction while in the runner to a direction parallel to the shaft; and the propeller type, in which water passes through the turbine parallel to the axis of the runner. In both Francis and vertical propeller type turbines, water is distributed to the runner by a spiral scroll case which directs water flow to the blades of the runner through stay vanes and wicket gates. In modern application, the Francis type is generally used at heads greater than 30 metres, while the propeller type is generally used where heads are less than 30 metres. The Kaplan turbine is a special design of the propeller type wherein the pitch of the turbine blade is adjustable.

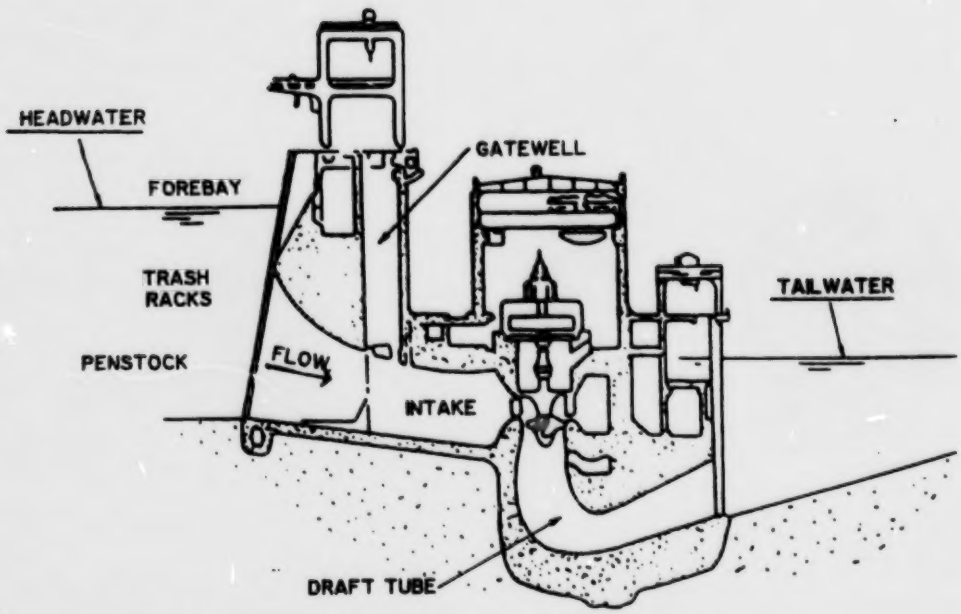


FIG. 1. Cross sectional view of typical large Kaplan turbine (source - Long & Marquette 1967).

Horizontally mounted variations of the propeller turbine are bulb and tube types where the shafts are in tubular housings without spiral cases. Figure 2 illustrates the essential features of typical Francis and Kaplan turbines, indicating the relative positions of the runners, scroll case, guide vanes, wicket gates and draft tube. Details of the Fourth Lake tube type turbine are presented in a latter section of this report.

In both Francis and propeller type turbines, all water passages are enclosed and are completely filled with flowing water under pressure. The transfer of energy from the water to the turbine runner is due to hydraulic pressure and to a change of flow direction against the blades. The setting of modern Francis and propeller turbines is usually with the shaft in a vertical position, although in several of the smaller, older units, horizontal installation is common. Bulb and tube turbines are mounted in a horizontal position. The physical size of turbines is relative, based on equivalent power output. Installations at higher heads require less water to produce an equivalent amount of power and hydraulic passages are accordingly smaller. The number of blades in a Francis runner varies from 14 for low heads to 20 for high heads. Propeller turbines usually have 4 to 6 blades and clearances between blades on these runners is correspondingly greater than on Francis runners.

The wicket gates are rotated about a vertical axis and act to control the amount of water entering the turbine and hence the power it produces. At the most efficient opening, wicket gates constitute a continuation of the guide vanes which are structural elements that

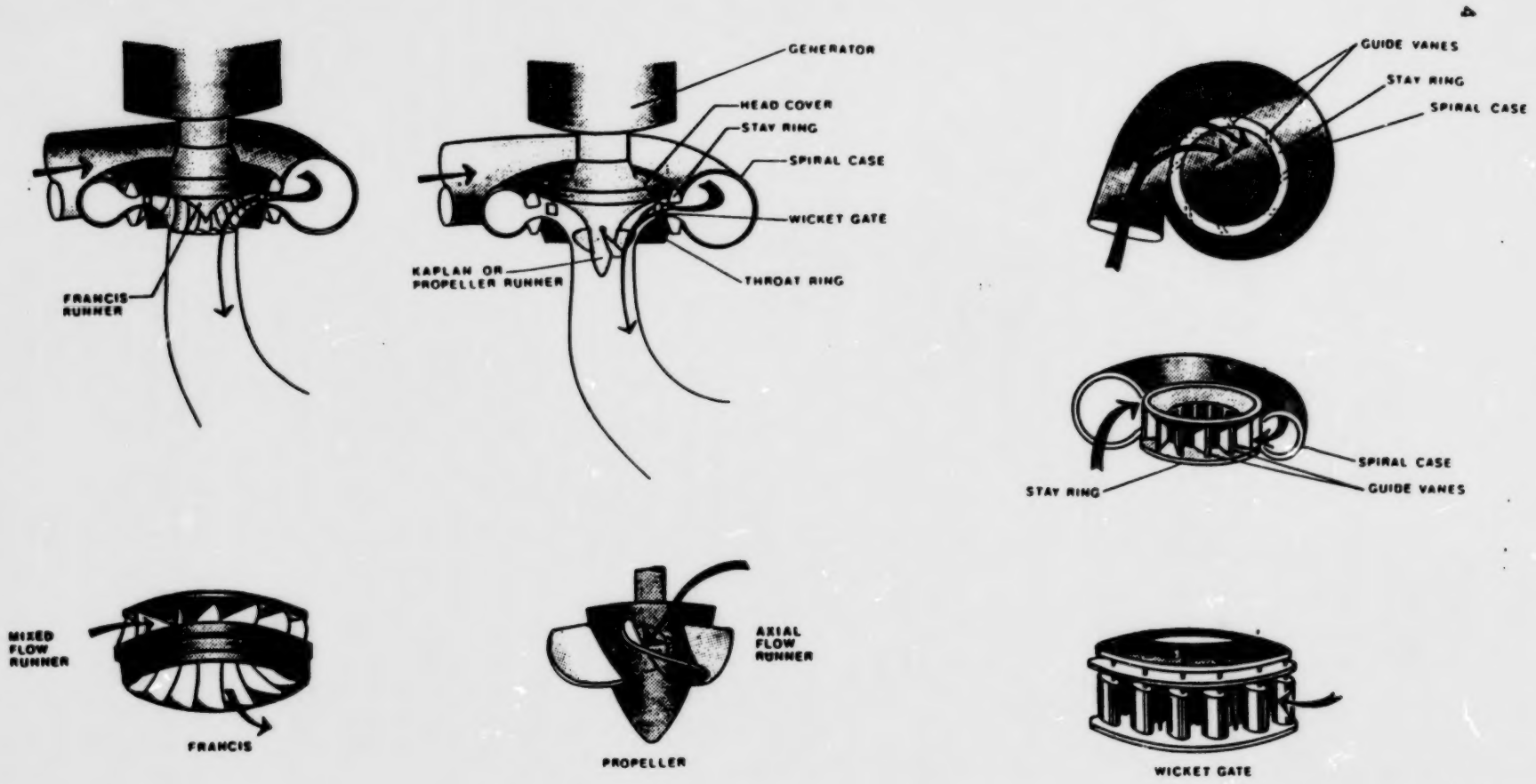


FIG. 2. Details of typical Francis and Kaplan turbines.

impart a whirling motion to the water as it passes to the runner. Clearances between guide vanes, wicket gates and turbine blades will vary depending upon the wicket gate opening required to supply the necessary water for the load the turbine is carrying. Water from the discharge side of the turbine runner is returned to the river by the draft tube.

Water velocities are relatively slow and pressures positive in water passages leading to a turbine. Velocity then increases through the turbine. The turbine runner, when developing power, will have its blades traveling in the same direction as the flow and at an average speed which is less than the velocity of the incoming water. Water velocities quickly decrease after passing through the turbine and negative pressures may develop depending on the relative elevation of the turbine to the tailwater. Turbine runners are normally set at an elevation to avoid local negative pressures that would cause cavitation. Cavitation occurs when vapour masses collapse and by so doing, create small localized areas of intense negative pressures violent enough to remove small particles of metal from the turbine blades. A more detailed description of cavitation is presented below.

In Francis turbines with high velocity flow through the guide vanes and wicket gates, mechanical injury to fish may occur when clearances between wicket gates and leading edges of the turbine blades are small in relation to fish size. Because of the large clearances between the 4 to 6 blades of propeller type turbines, there is less opportunity for direct mechanical damage within the wheel; although a variety of shearing forces may cause physical damage to fish as they pass near the blade edges.

DESCRIPTION OF CAVITATION, SIGMA AND UNIT HORSEPOWER

Cavitation results from the violent collapse of vapour pockets when they pass into areas of higher pressure. The vapour pockets are formed where a localized or general reduction in pressure causes the water to vaporize, forming cavities filled with vapour. This reduction in local pressure may be caused by either a decrease in ambient pressure or an increase in local velocity. Vapour pockets and cavitation can occur along the blade and blade edges as well as beyond the trailing edges of the blades. The violent collapsing of vapour bubbles generally results in noise, vibration and rough operation. If these bubbles collapse near a surface of the water passageway, they may cause extremely high localized stresses that eventually remove material from that surface. The absence of cavitation damage in a turbine runner does not imply cavitation is not occurring beyond the trailing edges of the blades. However, turbine runners which show signs of cavitation damage are believed to have a greater potential to kill fish (Muir 1959, Bell 1984). The potential for cavitation is generally highest when heads or loads are below or above optimum. However, turbine runners which show

sigma of cavitation damage are believed to have a greater potential to kill fish (Muir 1959, Bell 1984). The potential for cavitation is generally highest when heads or loads are below or above optimum.

Sigma and unit horsepower are variables used by turbine engineers to ensure the absence of extreme cavitation in their designs. Sigma refers to the elevation of the turbine runner in relation to the tailwater and is directly proportional to the difference between suction pressure and vapor pressure (Fisher and Cybularz 1987). Unit horsepower refers to the power derived from a runner one foot in diameter under one foot of head. Before model test stands were available to determine the cavitation characteristics of a particular design, specific speed was used to estimate required turbine settings.

Sigma is a dimensionless parameter used to define the required depth of the turbine centerline in relation to the tailwater level, referred to as turbine setting, and net head. Sigma can be calculated by:

$$\sigma = \frac{Ha - Ht}{Hp}$$

Where Ha is the barometric pressure minus the vapour pressure of water at the turbine. Ht is the vertical distance from the centerline of the turbine runner to tailwater (if runner is below tailwater, Ht becomes negative). Hp is the net head at the plant.

The deeper the relative turbine setting (higher sigma) the lower the potential for cavitation. In general, higher head plants will require a greater submergence than low head plants to maintain the same sigma value to avoid cavitation. However, sigma is not the only measure of cavitation potential. The other is runner design, which cannot be quantified. Hence, a high head plant with a lower sigma value could have the same protection against cavitation as a lower head plant with a higher sigma value.

Turbine runners are normally set at an elevation sufficient to avoid excessive cavitation that would lead to blade destruction. With normal turbine settings, localized areas of negative pressures and cavitation remain but do not generally affect a large proportion of the fish passing through the turbine. The small increase in tailwater level, usually less than 1/2 m, which results from higher flow through the turbine at full gate opening, is generally insignificant in relation to the increase in cavitation potential. Higher tailwaters, of more than several meters increase, which may occur during flood level flows, are often sufficient to reduce or eliminate cavitation.

The specific design characteristics of different turbine runners can be compared by reducing the head and diameter to unit values, i.e. the horsepower developed by a turbine with a runner one foot in diameter under one foot of head. Unit horsepower can be calculated as follows:

$$HP_{11} = \frac{HP}{D^2 \quad H^{3/2}}$$

Where D = throat diameter
H = rated head
HP = rated horsepower
HP_{11} = horsepower @ 1 foot diameter and 1 foot head

The greater the unit horsepower, the deeper the required setting of the turbine in relation to tailwater (larger sigma). Propeller turbines require deeper turbine settings than Francis turbines of similar unit horsepower. Increases in runner diameter will lower the unit horsepower of a turbine and, thus, reduce the potential for cavitation. Increasing the runner diameter has been suggested as a means to reduce the potential for cavitation damage to fish passing through a turbine (Muir 1959).

SITE LOCATION AND TURBINE DESCRIPTION

The Fourth Lake hydroelectric development is located on the Sissiboo River at a location about 30 km upstream of the village of Weymouth, Nova Scotia (Figure 3). The generating plant is located below an earth filled dam located at the outlet of Fourth Lake. The plant began operating in 1983 and the "S-turbine" experienced cavitation problems at high heads and 100% gate openings. Therefore, the normal operation restricts gate opening to 80%.

Flow is derived from a drainage area of 260 km^2. Fourth Lake is impounded by a main dam and four wing dams which create a total reservoir capacity of 146 x 10^6 m^3. Water from the reservoir is delivered to the turbine through a 82 m long steel lined concrete penstock. An overall layout of the Fourth Lake hydroelectric development showing the fish introduction and recapture locations is presented in Figure 4.

The single horizontal "S-turbine" was designed by Escher-Wyss and built by Dominion Bridge - Sulzer. The turbine develops a maximum of 4,000 hp under a rated head of 22.7 m and a flow of 15.1 m^3/s. The turbine and generator operate at 360 rpm, with a rated output of 3.1 MW. Figure 5 provides a schematic view of the turbine components, while Figure 6 is a cross section of the runner. Table 1 summarizes available design parameters.

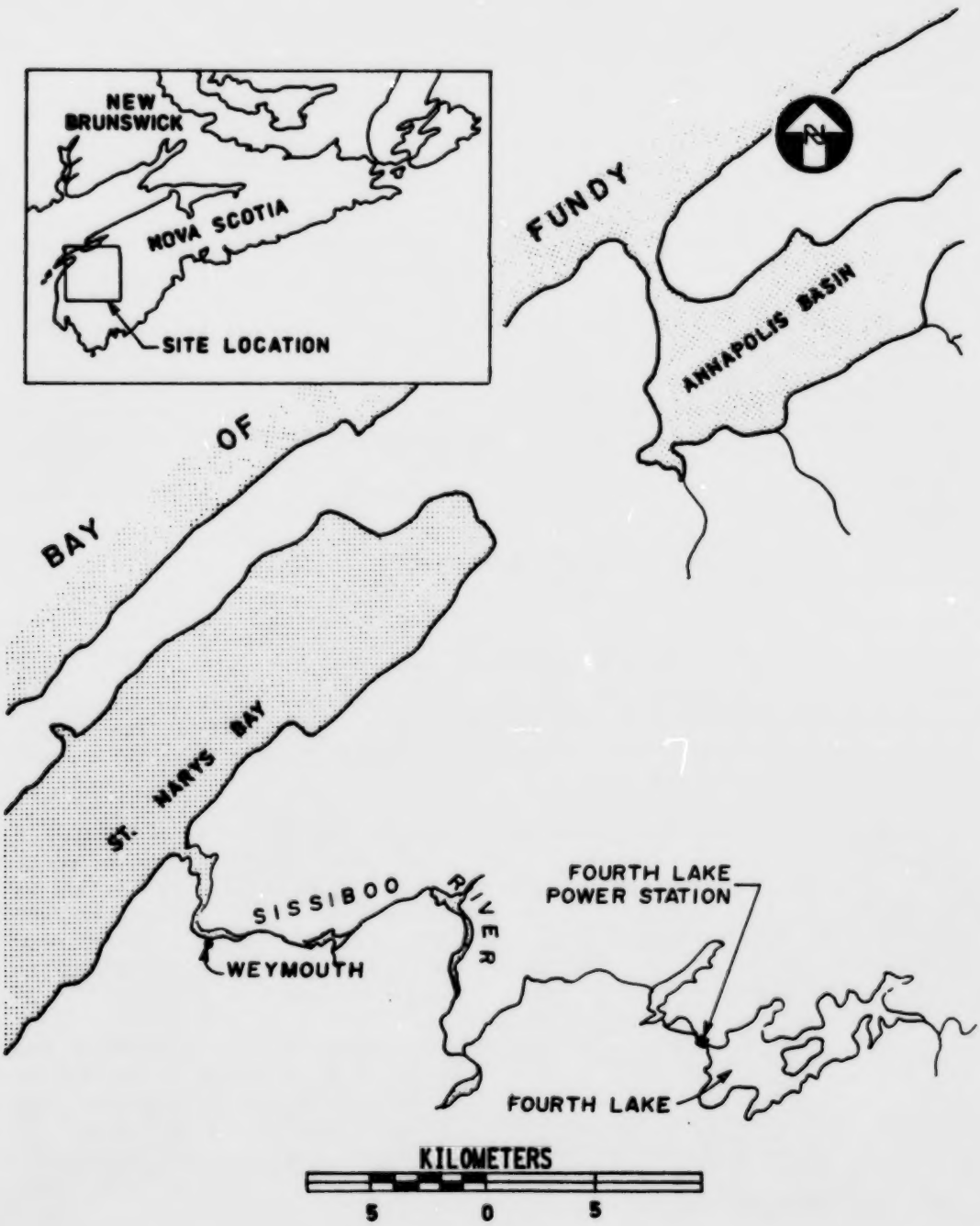


FIG. 3. Site location.

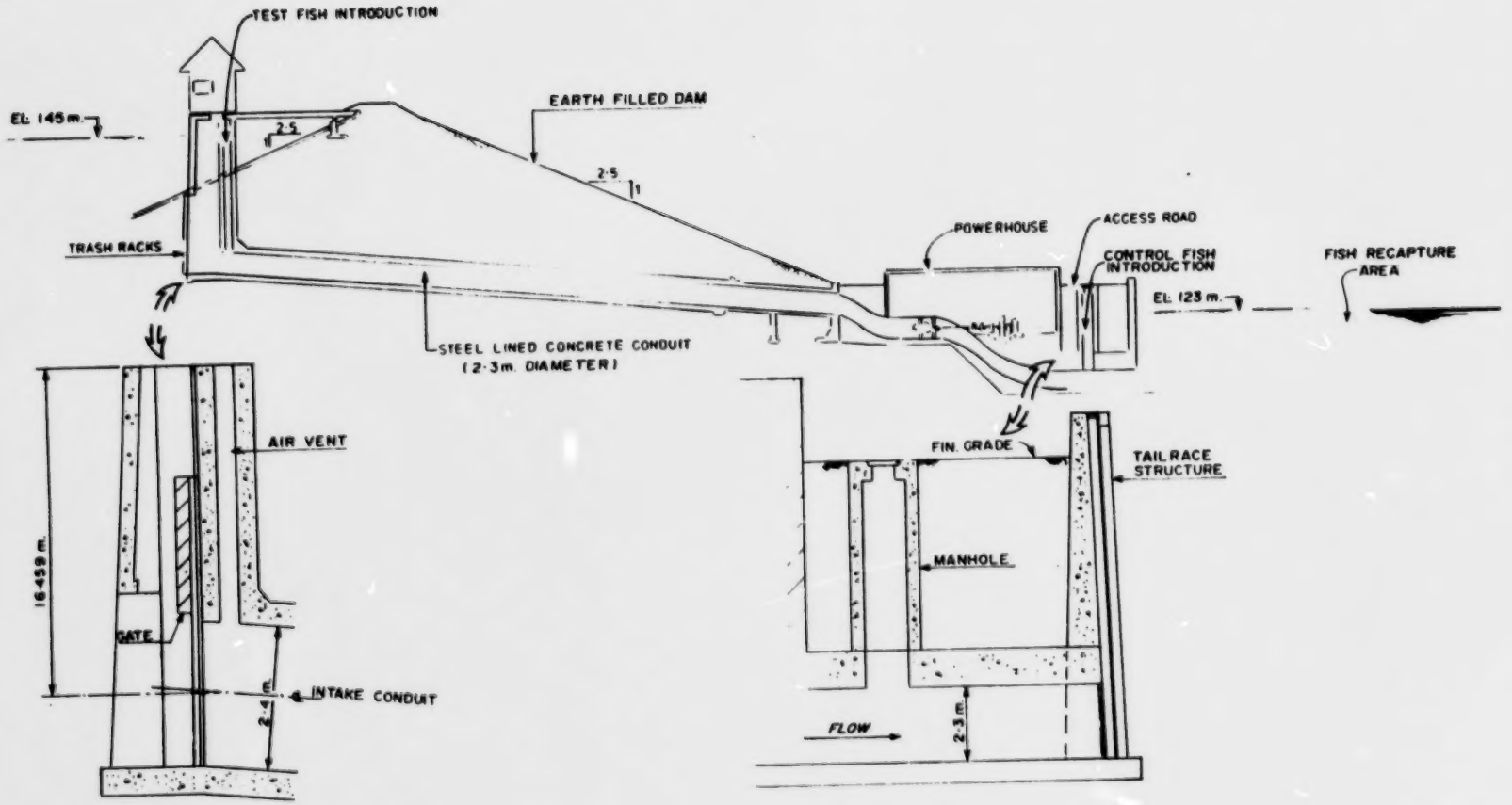


FIG. 4. Layout of the Fourth Lake power station showing locations of fish introduction and recovery.

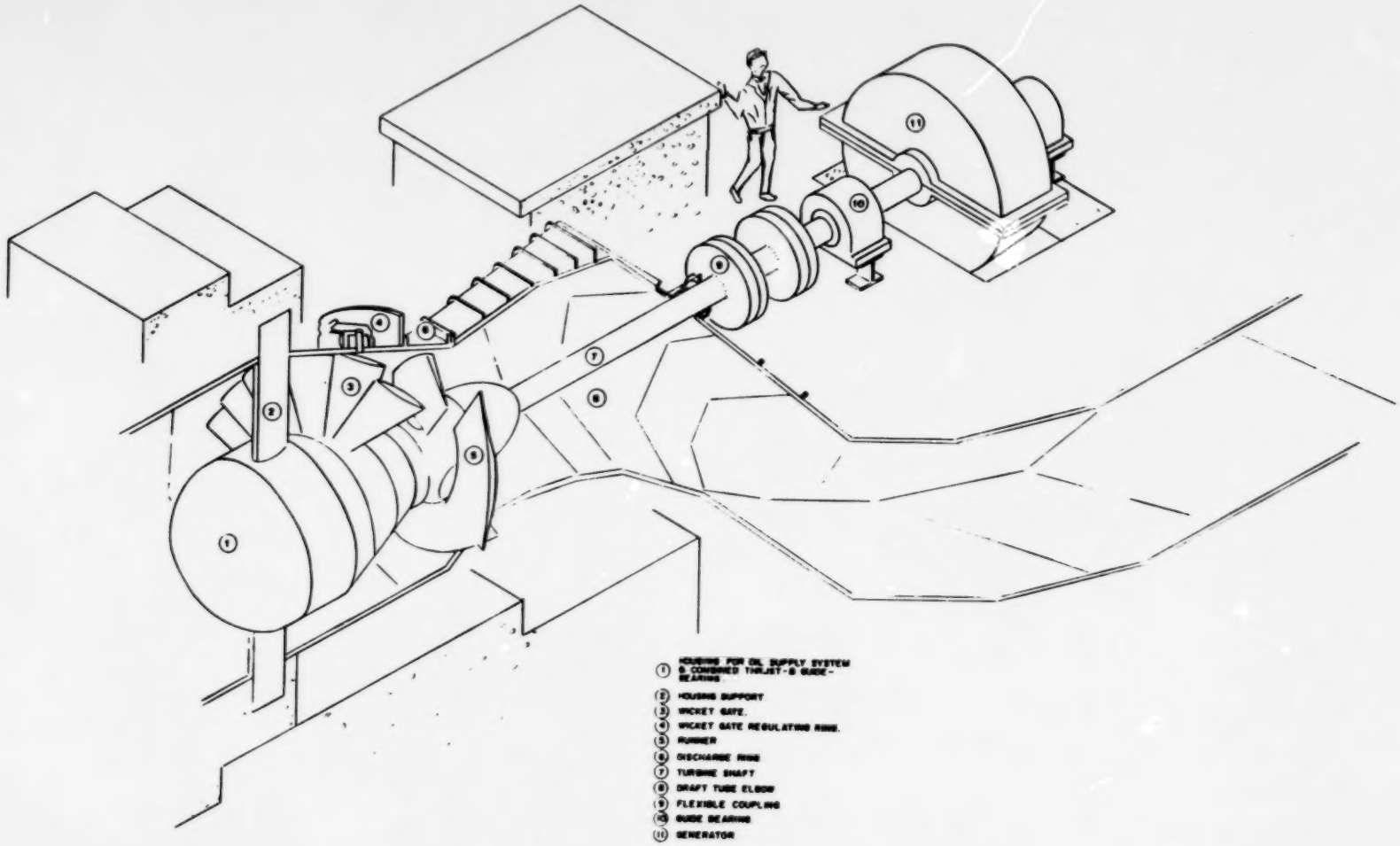


FIG. 5. Schematic representation of Fourth Lake S-turbine.

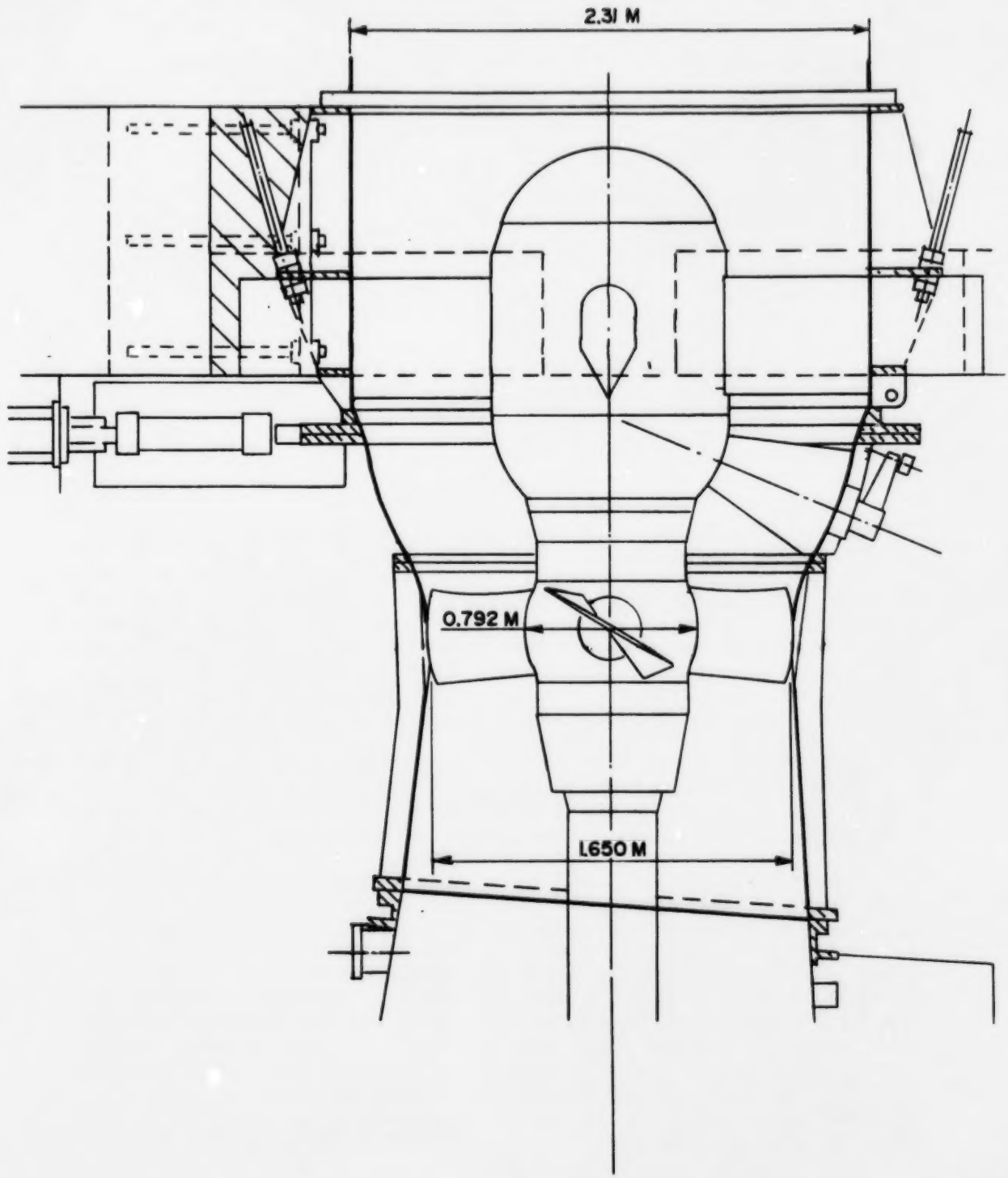


FIG. 6. Cross section of Fourth Lake runner.

TABLE 1 - Specification of the Fourth Lake Turbine.

1.	Type of Turbine	Tube (S-Turbine)
2.	Rated Head	23 m
3.	Rated Speed	360 RPM
4.	Number of Wicket Gates	13
5.	Number of Runner Blades	6
6.	Runner Diameter	1.65 m
7.	Hub Diameter	0.79 m
8.	Peripheral Velocity [1]	32.1 m/s
9.	Incidence Angle (α) [2]	25°
10.	Discharge	15 m^3/s
11.	Rated Output	3.1 MW
12.	Runner Elevation Above Tailwater	-1.1 m

1. The speed of runner movement at its periphery.
2. The approximate angle formed by the water flow with the axial direction of the runner at 80% wicket gate opening.

METHODS

Groups of juvenile brook trout (Salvelinus fontinalis) and juvenile alewife (Alosa pseudoharengus) were released into the penstock during the test period and recovered in a fish recapture net that strained virtually the entire tailrace discharge. Control fish were treated identically to test fish and were introduced near the exit of the draft tube. Testing in 1986 revealed that control releases in the exit of the draft tube and those released just upstream of the recapture net suffered the same mortality. Thus control releases were available to correct for handling and fish recapture mortality.

In addition to these experimental releases of fish, some local populations of alewife and yellow perch (Perca flavescens) left the Fourth Lake reservoir by way of the turbine flow. Recapture of these fish allowed additional estimates of turbine mortality to be calculated.

Trout were supplied by the Nova Scotia Department of Fisheries from their McGowan Lake Hatchery. Fish were delivered weekly by federal Department of Fisheries and Oceans fish transport trucks with little or no mortality during transportion. About 500 adult alewife were transported from the Tusket River and introduced into the Fourth Lake headpond in May. The hope was that these fish would reproduce and provide a natural run of juveniles that would migrate seaward during the period August - October. When these fish did not show up during August and early September, juvenile alewife were transported from the Tusket River by Department of Fisheries and Oceans personnel. These fish suffered fairly extensive transportation mortality (estimated to be from 10 to 30 percent). Subsequent to transporting juvenile alewife from the

Tusket River, progeny from the adult transfer began to be entrained by the turbine flow about mid September. Perch were entrained throughout the duration of the testing period and were held for later test and control introductions.

Trout, alewife and perch were held in 1.2 m x 2.4 m x 0.6 m holding pens in the headpond. All fish used in turbine mortality experiments were held at least 24 hours prior to testing to allow for recovery from fish transportation stress. None of the fish were fed during the holding period. Test and control trout were held for up to seven days to measure delayed mortality. Attempts to hold alewife were unsuccessful and an evaluation of delayed mortality for these delicate fish was abandoned.

Test and control trout were sorted into two size class groups of approximately 100 fish, except for five tests when only one size class was used. Fish were marked by cold branding or fin clipping. Trout were anaesthetized by immersion in MS 222 and cold branded by 6 mm high silver brands cooled by liquid CO_2. The technique used followed methods similar to those described by Raleigh et al. 1973. A choice of seven brands on the left or right side between operculum and dorsal fin allowed distinctive marks of each group of test and control fish. Fish were marked one or two days prior to testing to allow for the brands to become distinct and for the fish to fully recover before subjecting them to turbine passage tests. Test and control groups were then introduced simultaneously into the penstock and draft tube exit.

After recapture, trout were returned to the holding pens. Live fish were anaesthetized, sorted and measured the following day. Trout were held for at least one week after which they were returned to the hatchery for subsequent stocking. Dead fish were immediately measured and injuries recorded. Deaths during the week of holding were treated in the same manner. Very few trout died as a result of branding or holding prior to testing.

Test and control alewife were marked by using a fluorescent powder spraying technique developed by A. Ducharme, Fisheries and Oceans Canada. Fish were marked immediately prior to their release into the penstock or draft tube. Upon recovery in the fish recapture gear, fish were sorted into two groups: live and a second group, that included dead, severed and injured fish. The alewife were not measured prior to release so as to avoid additional handling stress. All recaptured alewife were measured.

Perch that had been entrained by the turbine flow, captured in the recapture gear, and held in the live boxes in the headpond, were used for test and control releases during two turbine tests. In the first test, immersion dyes (Neutral Red and Bismark Brown) were used to mark test and control fish. The staining techniques were similar to those

described by Taylor and Kynard 1985. In the second test, test and control fish were fin clipped. Fish that were recaptured alive in both these tests were held for 24 hours to observe delayed mortality.

The introduction of test and control fish was coordinated with a previously arranged schedule for operating the turbine at specific wicket gate openings. Prior to the test routine beginning, all fish and debris were removed from the fish recapture gear. About 15 minutes prior to the release of fish, the turbine was set at the desired setting. Fifteen minutes after release of test and control fish, the turbine was brought up to 80% gate opening (during those tests when the gate opening was below this setting). This helped flush fish into the recapture gear. After about an hour the turbine was shut down and fish were removed from the fish recapture gear. In most cases, the live box was re-emptied after three or four hours to capture any fish that held up in a pool area directly above the fyke net. The turbine operated at 80% gate during this four hour period.

Test and control fish were introduced by means of a 10 cm diameter plastic pipe. A pail and short section of 15 cm pipe were fastened to the top of the narrower pipe and a plywood plug inserted to retain water while the fish were added (Figure 7). Fish and water were released by pulling the plywood plug out of the pipe in the bottom of the pail. Introductions of all test and control fish were carried out using similar pipe systems and procedures to ensure valid control results.

Test fish were introduced into the penstock through the gate slot at the entrance of the penstock. Control fish were introduced through a gate slot near the exit of the draft tube tunnel. Virtually the entire flow from the turbine discharge was strained by a modified fyke net made of 1.3 cm stretched mesh nylon netting connected to a floating live box by a 20 cm diameter flexible hose (Figure 8). The fish recapture gear was developed from descriptions of salmonid field trapping methods that had proved successful in the western U.S. and Canada. Steel framing was anchored to the stream bed about 30 metres downstream of the exit of the draft tube tunnel and the netting attached with 9.5 mm shackles through the headropes. Gaps below and at the sides of the framing were screened with mesh to ensure complete straining of the discharge.

The primary concern in the design of the recapture gear was the recapture of fish alive and uninjured. The principal components of the gear were similar to those described by Ruggles and Collins (1981). The downstream surface area of the fyke net was increased by expanding the net taper to increase the net area and hence reduce flow through the flexible hose leading to the live box. This portion of the net was held in shape by a steel cage. Recapture of control trout confirmed low injury rates for this species (average mortality 3.3%) but control alewife releases suffered an average of 37% fish handling and recapture mortality.

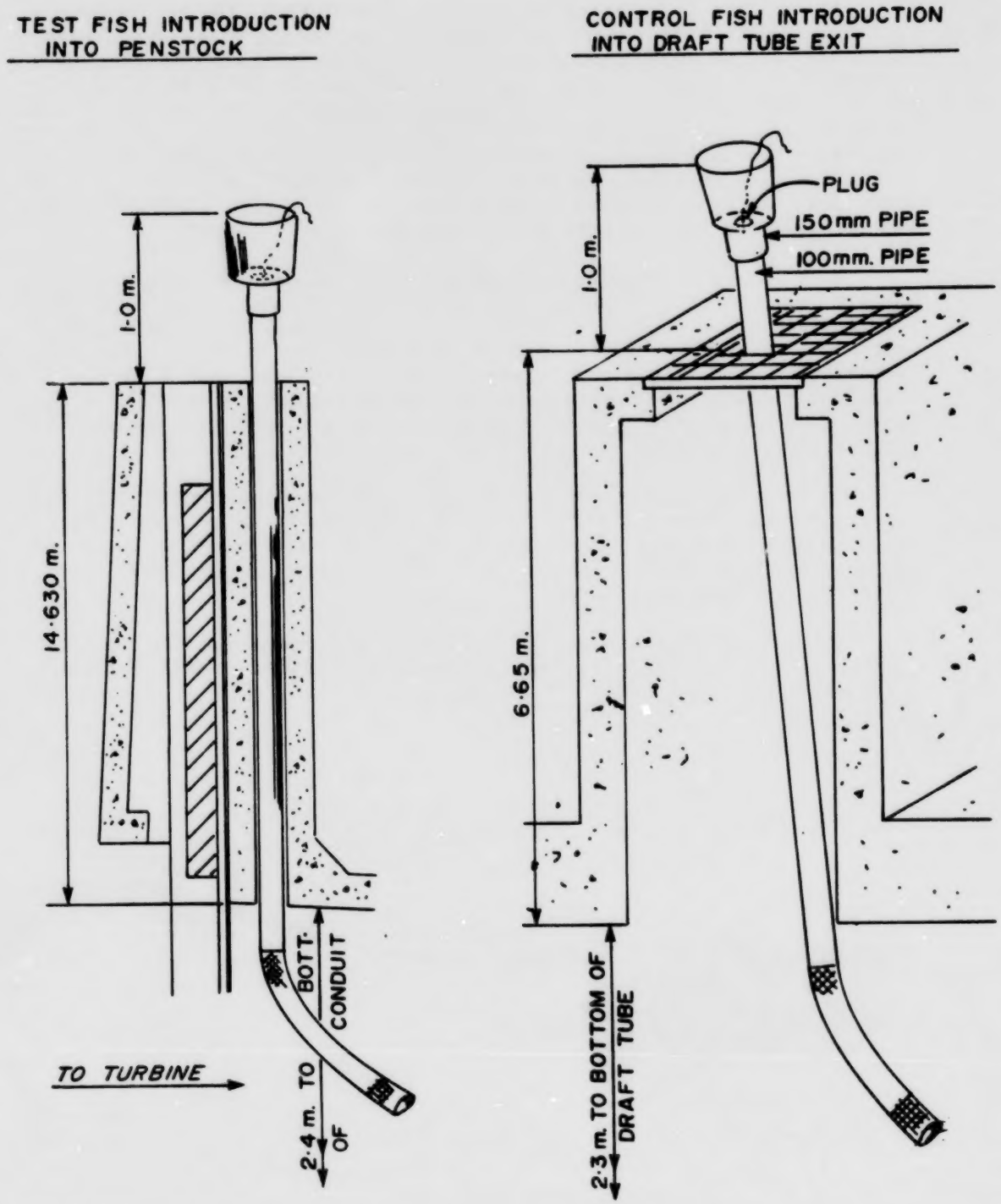


FIG. 7. Fish introduction apparatus.

In addition to recapturing test and control fish, the recapture net also caught fish that were entrained by the turbine flow originating from the Fourth Lake reservoir. Seaward migrating alewife that were progeny of an adult transfer into the headpond in May were recaptured along with several strictly freshwater species. Yellow perch and alewife left the reservoir in sufficient numbers by way of the turbine discharge to allow mortality estimates of these natural migrating populations to be made. Mortality of these naturally migrating fish in the recapture gear appeared to be quite low provided they were not held in the gear for long periods (i.e. overnight).

Mortality and injuries were examined in relation to species, fish length, wicket gate opening, and water temperature. The main test species was brook trout. Other species (alewife and yellow perch) were not as available and/or proved difficult to handle under the experimental conditions that prevailed at Fourth Lake, and analysis of some variables with these species was not possible. A total of 4,917 trout, 1,325 alewife and 693 yellow perch was utilized during the conduct of the research.

To investigate the effect of fish length, test and control releases of trout were separated into two size categories based on fork length. In addition, the mean length of each test release group was used in regression analysis to examine the relationship between fish size, mortality and type of injury.

To examine the effect of turbine wicket gate opening on fish mortality and injury type, the turbine was operated at the following gate settings: 100%, 80%, 67% and 40%.

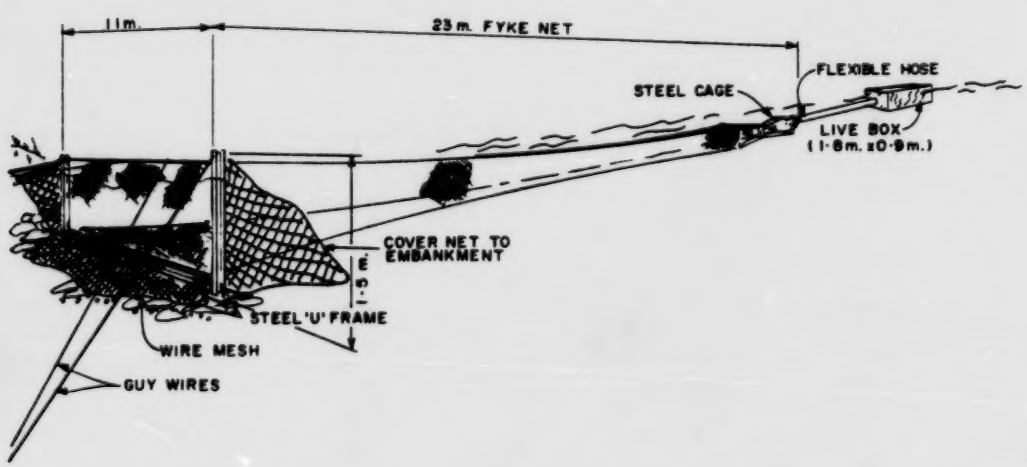


FIG. 8. Fish recapture gear.

Water temperature was recorded daily during the duration of the test period at the time of each test.

Several releases of dead control trout were made to examine the recapture efficiency of dead trout exiting the draft tube.

Because of a difference in susceptibility to recapture of trout and alewife, two methods of calculating the proportion of fish killed by turbine passage were used.

Some trout that survived turbine passage and some of the live controls held up in a deep pool located between the exit of the draft tube and the mouth of the recapture net. Because the live control fish tended to hold up in this pool more than the live test fish, it was not possible to use simple proportions of live recaptures to calculate corrected turbine mortality as is often done in turbine fish passage research utilizing recapture of test and control fish (Bell et al. 1967, Ruggles and Collins 1981).

Trout mortality due to turbine passage can be calculated by means of the following formula:

$M = [\text{overall } M - \text{control } M + (M \times \text{control } M)] \times 100$

where M = percent of fish killed by turbine effects only.
overall M = fraction of dead fish recovered in a test group corrected for non recapture of dead fish.
control M = fraction of dead fish recovered in the accompanying control group.

The need for adding the function (M x control M) to the adjustment formula is to take into account that fish killed by the turbine are removed from the population exposed to risk in the recapture gear.

The control mortality was calculated by dividing the total number of dead control fish recaptured by the total number of live control fish released. By releasing dead control fish, the recapture efficiency of dead fish was estimated. The overall number of dead test fish recaptured in each test was adjusted by using correction factors derived from the release of dead controls to account for dead fish not recaptured in the gear. Then the overall mortality was calculated by dividing the total adjusted number of dead test fish recaptured by the total number of test fish released.

No correction of dead control fish was used because it was assumed that control fish had died in the recapture gear; hence, were completely vulnerable to recapture. It was further assumed that control fish released dead at the exit of the draft tube and test fish killed in the turbine were equally susceptible to recapture.

Transposing, the above equation:

$$M = \frac{(\text{overall M} - \text{control M})}{1 - \text{control M}} \times 100$$

This was the formula used to calculate the percent of trout killed by turbine passage.

Alewife, from either test or control releases, did not tend to hold up upstream of the recapture net. Thus, turbine induced mortality of alewife test fish was estimated by comparing the ratio of the fraction of recaptured test fish to the fraction of recaptured control fish by the following formula:

$$M = \left(1 - \frac{St}{Sc}\right) \times 100$$

where M = percent of fish killed by turbine effects only
St = fraction of live fish recovered in a test group
Sc = fraction of live fish recovered in the accompanying control group

Estimates of turbine mortality for entrained alewife and perch were calculated by dividing the total number of dead fish captured by the total number of live and dead fish captured by the recapture gear. These mortality estimates did not correct for any mortality inflicted by the recapture process, or for the non-recapture of live or dead fish.

Data analysis was carried out using the Statistical Package for the Social Sciences (SPSS) programs on the CDC computer at the Technical University of Nova Scotia. Computer files containing the length frequencies of all released and recaptured fish, injury frequencies and mortalities were prepared. Initial stages of analysis included statistical tests to investigate deviations in length frequency between released and recaptured fish and live and dead recaptures. The variations in length frequencies were then compared to the percentage recaptures to determine whether all tests could be treated in an identical manner. All percentage data were arc sine transformed prior to statistical analysis.

Factor analysis was used to investigate correlations between injury types, turbine operating conditions and other variables such as delay in recapture and fish length. Injuries were examined separately and in groups.

Analysis of mortalities was completed in the final stages. Multiple regression and comparison of means were the primary methods used.

RESULTS

Twenty-five valid trout tests and five valid alewife tests were conducted between September 3 and October 27, 1987. A few tests (three) were considered invalid when the fish recovery gear was not fished for a sufficiently long period (usually over a weekend) to capture test fish, or when large holes in the recapture gear allowed test and control fish to escape. Two tests were invalidated by the capture of large numbers of wild alewife that prevented an orderly assessment of experimental and control recaptures and which also resulted in the suffocation of fish in the recapture gear livebox.

A total of 4,917 trout and 1,325 alewife were used in these experiments. Overall recapture rates were 45% for trout and 83% for alewife. Control mortality averaged 3.3% for trout and 37% for alewife. In addition, 11,955 alewife and 729 yellow perch were captured after they had left the headpond on their own volition and passed through the Fourth Lake turbine. In the case of the perch, fish were held and later released in two tests. The recapture rate for these perch tests was 70%. Fish size did not influence rate of recapture for trout, alewife or perch.

Recapture of dead control trout was influenced by gate setting ($p = .004$). The regression was used to estimate the recapture rate of dead trout for each gate. The following summarizes this relationship and presents the correction factor used to adjust the recapture of dead test fish for each gate.

Gate Setting	Recapture Rate	Correction Factor
100%	99%	1.01
80%	84%	1.19
67%	73%	1.37
40%	50%	2.00

TROUT MORTALITY

The effects of fish length, gate setting and water temperature on trout mortality were examined by step-wise multiple regression analysis with fish length, gate setting and water temperature representing independent variables. To meet the assumption required in regression analysis, all values of fish mortality were transformed using the arcsine transformation. The only significant variable was water temperature (Appendix A). The relationship between water temperature and turbine induced trout mortality is shown in Figure 9. Even though the relationship is significant ($P = .017$), the data are extremely variable and the degree of variability increases with higher temperature. Temperature accounts for 18% of this variability.

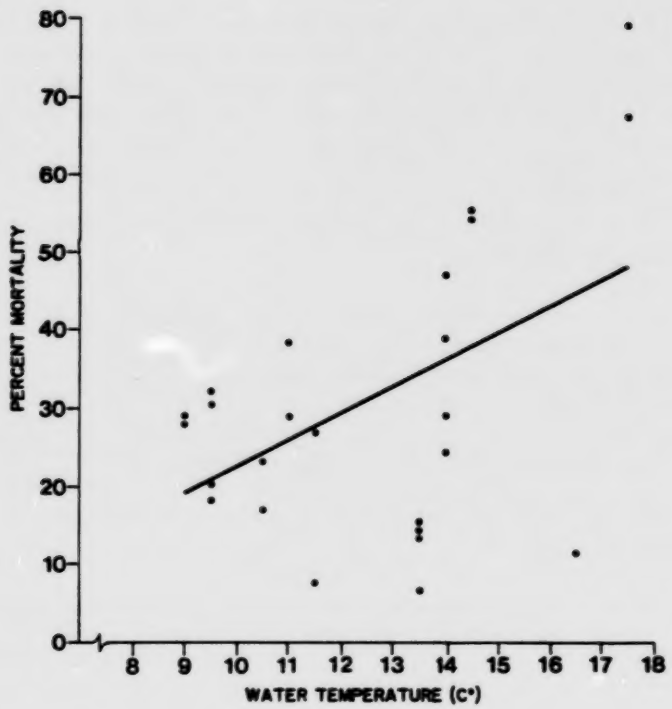


FIG. 9. Relationship of trout mortality to water temperature.

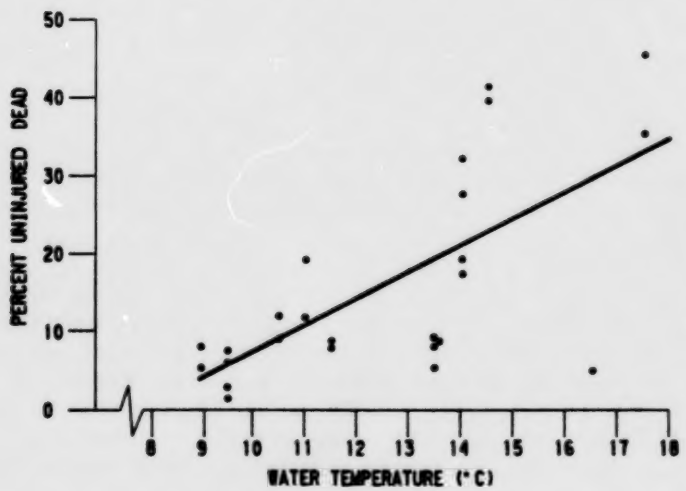


FIG. 10. Relationship of "uninjured" dead trout to water temperature.

The effect of water temperature on mortality of those test fish recaptured dead but having no apparent injuries was then examined. It was reasoned that these "uninjured" dead test fish were probably responsible for most of the effect of water temperature, since it was unlikely that water temperature would influence the degree of mechanical injury. The influence of water temperature on that component of trout mortality not showing visible physical injury is shown in Figure 10. The relationship is highly significant (P = .001). Water temperature now accounted for 44% of the variation in these data.

Because of the possibility that temperature might have masked the effects of fish length and turbine gate setting, fish mortality data were re-examined over a narrower temperature range. When tests conducted at temperatures above 14°C were removed from the data set (five tests) water temperature was no longer significant (P = .73). Regressions of fish length and gate setting against fish mortality were still not significant in this data set (P = .28 for length and P = .60 for gate).

In addition to water temperature, fish length and gate setting influenced the number of "uninjured" dead trout that made up the mortality estimate for any given test. Fish length accounted for 30% (P=.004) and gate setting 20% (P=.027) of the variability. The number of "uninjured" dead test and control trout increased with wicket gate setting and decreased with the mean length of the test and control trout (Appendix A).

Various injury types were then examined to see if any relationships existed between the type of injury and either fish length or gate setting. The only significant relationship (P = .015) that immerged was between severed trout and their mean length (Figure 11). Once again, the high variability of these data is evident, with 23% being attributable to length.

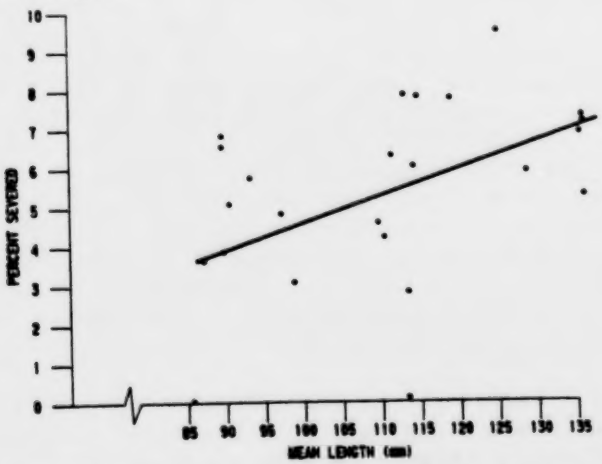


FIG. 11. Relationship of severed trout to mean length of released trout.

In order to derive an average trout mortality estimate for comparisons with other species within the present study and for external comparisons with salmonid mortality estimates of fish passage in other turbine types, a mean trout mortality was calculated excluding the five tests conducted at temperatures above 14°C. The mean trout mortality for this data set was 24.7%.

A summary of the total valid trout tests (25) is provided in Table 2.

MORTALITY OF TRANSPORTED ALEWIFE

Regression analysis involving gate setting, water temperature, and fish length with mortality and various injury types, failed to establish any relationships at the 5% probability level for the test alewife that had been transported from the nearby Tusket River. However, the relationship between the number of alewife severed and the mean length of the recaptured dead was almost significant ($P = .06$). Since alewife were not measured prior to recapture, the mean length of the released test fish was unknown.

The five valid tests of transported alewife are summarized in Table 3. The mean mortality for these five tests is 66.5%.

MORTALITY OF ENTRAINED ALEWIFE

On ten occasions estimates of turbine induced mortality of naturally migrating juvenile alewife could be calculated. This occurred when these natural migrants were encountered in the fish recapture gear after the termination of a specific test. Most of these fish were assumed to have passed through the turbine when it was operating at 80% gate at a time when the test fish were being flushed into the fish recapture gear.

Table 4 summarizes the available information on these entrained alewife and presents estimates of turbine induced mortality. These estimates are not corrected for recapture mortality and assume equal recapture of live and dead alewife. This latter assumption appears valid on the basis of examining the recapture of test alewife where complete recapture of test fish occurred. Mortality inflicted by the recapture gear probably accounts for some of the fish that were killed, however, it is impossible to estimate what proportion this would be. Thus, the estimates of mortality are believed to be somewhat higher than attributable to turbine effects only. The average mortality estimate for these entrained naturally migrating juvenile alewife is 14.0%.

Regression analysis of fish length and water temperature on entrained alewife mortality gave no significant relationship. In Figure 12, the relationship between severed alewife and their mean length is

TABLE 2

Summary of valid trout tests.

TEST	DATE	WATER TEMP. (C)	GATE (%)	1 TYPE	2 SIZE	NUMBER RELEASED	MEAN 3 LENGTH (mm)	NUMBER SEVERED	WHOLE DEAD 4 INJURED	WHOLE DEAD 4 UNINJURED	TOTAL DEAD	NUMBER LIVE	MORT.5 %	ESTIMATED6 MORT.
5	14/09/87	17.5	67	T	N	102	89.2	7	7	46	60	26	58.6	79.1
				C	N	86	93.2	0	0	6	6	11	7.0	
6	15/09/87	17.5	67	T	N	107	89.2	7	7	39	53	20	49.5	67.2
				C	N	103	88.7	0	0	2	2	7	1.9	
7	16/09/87	16.5	67	T	N	112	85.5	4	2	5	11	7	9.8	11.8
				C	N	108	85.3	0	0	2	2	14	1.9	
9	23/09/87	14.5	80	T	L	98	97.8	3	4	39	46	7	46.9	55.4
				C	L	103	97.1	0	0	1	1	18	1.0	
9	23/09/87	14.5	80	T	S	107	75.0	0	6	44	50	5	46.7	54.4
				C	S	117	78.8	0	0	3	3	21	2.6	
12	30/09/87	14.0	80	T	L	99	113.7	6	3	17	26	50	26.3	24.6
				C	L	90	112.6	0	2	6	8	8	8.9	
12	30/09/87	14.0	80	T	S	104	92.4	6	3	34	43	31	41.3	47.1
				C	S	99	91.3	0	0	4	4	9	4.0	
13	01/10/87	14.0	80	T	L	109	109.4	5	2	21	28	43	25.7	29.8
				C	L	95	108.1	0	0	1	1	12	1.1	
13	01/10/87	14.0	80	T	S	105	89.3	4	5	29	38	35	36.2	39.0
				C	S	90	90.1	0	0	6	6	6	6.7	
14	05/10/87	13.5	80	T	L	95	111.1	4	3	7	14	22	14.7	16.0
				C	L	107	108.2	0	0	2	2	38	1.9	
14	05/10/87	13.5	80	T	S	96	85.6	0	3	8	11	22	11.5	6.7
				C	S	108	88.7	0	0	8	8	37	7.4	
15	06/10/87	13.5	67	T	L	103	118.3	8	2	6	16	30	15.5	15.6
				C	L	104	118.3	0	0	7	7	21	6.7	
15	06/10/87	13.5	67	T	S	123	97.4	6	0	10	16	14	13.0	13.5
				C	S	101	98.1	0	0	5	5	17	5.0	
16	13/10/87	11.5	67	T	L	103	114.7	8	4	9	21	34	20.4	26.7
				C	L	121	112.9	0	0	2	2	53	1.7	
16	13/10/87	11.5	67	T	S	99	90.7	5	0	7	12	34	12.1	7.9
				C	S	106	93.3	0	0	10	10	47	9.4	
18	19/10/87	11.0	67	T	L	98	136.5	7	2	19	28	49	28.6	38.5
				C	L	101	136.0	0	0	1	1	62	1.0	
18	19/10/87	11.0	67	T	S	95	112.6	6	5	11	22	40	23.2	29.1
				C	S	107	114.7	0	0	4	4	47	3.7	
19	20/10/87	10.5	100	T	L	102	135.5	7	3	9	19	46	18.6	17.0
				C	L	100	136.5	0	1	1	2	74	2.0	
19	20/10/87	10.5	100	T	S	101	112.6	8	5	12	25	49	24.8	23.2
				C	S	101	113.0	0	0	2	2	58	2.0	
23	26/10/87	9.0	40	T	L	95	136.3	5	3	5	13	36	13.7	29.5
				C	L	107	135.1	0	0	2	2	44	1.9	
23	26/10/87	9.0	40	T	S	106	113.6	3	4	8	15	31	14.2	28.8
				C	S	94	113.0	0	0	4	4	21	4.3	
24	26/10/87	9.5	40	T	L	42	135.3	3	0	3	6	15	14.3	32.1
				C	L	60	135.1	0	0	0	0	25	0.0	
24	26/10/87	9.5	40	T	S	49	113.1	0	1	3	4	43	8.2	18.4
				C	S	53	113.8	0	0	0	0	25	0.0	
25	27/10/87	9.5	40	T	N	95	125.0	9	1	3	13	29	13.7	30.8
				C	N	103	125.9	0	0	0	0	66	0.0	
26	27/10/87	9.5	40	T	N	101	128.4	6	1	2	9	39	6.9	20.1
				C	N	107	123.9	0	0	0	0	43	0.0	

1. T = TEST
   C = CONTROL

2. N = NO SIZE CLASSIFICATION
   L = LARGE SIZE CLASSIFICATION
   S = SMALL SIZE CLASSIFICATION

3. MEAN LENGTH OF RELEASED FISH

4. INJURED = WHOLE DEAD FISH WITH VISIBLE INJURY
   UNINJURED = WHOLE DEAD FISH WITH NO VISIBLE INJURY

5. % MORTALITY = (TOTAL DEAD/# RELEASED) X 100

6. MORTALITY FROM TURBINE EFFECTS

TABLE 3

Valid tests conducted with transported alewife.

TEST	DATE	WATER TEMP. (°C)	GATE (%)	[1] TYPE	NUMBER RELEASED	NUMBER SEVERED	WHOLE DEAD [2] INJURED	WHOLE DEAD [2] UNINJURED	TOTAL DEAD	MEAN [3] LENGTH (mm)	NUMBER LIVE	MEAN [4] LENGTH (mm)	MORT [5] (%)	EST. [6] MORT (%)
2	03/09/87	16.5	67	T	200	4	13	131	148	60.7	17	61.8	89.7	80.9
				C	201	0	5	33	38	62.1	45	63.1	45.8	
10	28/09/87	14.0	80	T	130	7	62	43	112	80.4	18	92.4	86.2	79.8
				C	149	0	10	33	43	84.4	94	84.5	31.4	
11	29/09/87	13.5	80	T	105	10	21	17	48	83.1	19	76.9	71.6	55.4
				C	104	0	13	23	36	80.1	63	82.0	36.4	
14	05/10/87	13.5	80	T	101	16	32	29	77	96.8	27	93.4	74.0	60.0
				C	113	0	13	20	33	97.2	61	98.3	35.1	
17	14/10/87	11.0	100	T	105	7	14	28	49	92.7	18	101.3	73.1	56.6
				C	117	0	4	23	27	96.1	44	102.4	38.0	
	Mean Mortality From Turbine Effects													66.5

1. T = Test
   C = Control
2. Injured = Whole Dead Fish With Visible Injury
   Uninjured = Whole Dead Fish With No Visible Injury
3. Mean Length of Recaptured Dead Fish
4. Mean Length of Recaptured Live Fish
5. % Mort. = (Total Dead / Total Recapture) x 100
6. Mortality From Turbine Effects

TABLE 4

Mortality estimates of entrained alewife.

OBSERVATION	DATE	WATER TEMP. (°C)	GATE[1] (%)	NUMBER SEVERED	WHOLE DEAD	TOTAL DEAD	MEAN[2] LENGTH (mm)	NUMBER LIVE	TOTAL CAPTURE	ESTIMATED[3] MORT. (%)
1	15/09/87	17.5	80	60	27	87	96.5	420	507	17.2
2	17/09/87	16.0	80	231	88	319	93.7	1504	1823	17.5
3	30/09/87	14.0	80	119	57	176	88.0	1362	1538	11.4
4	01/10/87	14.0	80	6	8	14	--	113	127	11.0
5	05/10/87	13.5	80	17	18	35	90.6	209	244	14.3
6	05/10/87	13.5	80	30	16	46	90.6	615	661	7.0
7	06/10/87	13.5	80	341	157	498	--	2463	2961	16.8
8	07/10/87	13.5	80	79	77	156	--	1200	1356	11.5
9	07/10/87	13.5	80	238	148	386	--	2040	2426	15.9
10	14/10/87	11.0	80	12	41	53	89.3	259	312	17.0
	Mean estimated mortality									14.0

1. Normal Turbine Operating Gate (80%)
2. Mean Length Of Captured Dead Fish
3. Estimated Mort. = (Total Dead / Total Capture) x 100

shown. Both transported and entrained alewife data are plotted in this figure and the relationship is significant (P = .05).

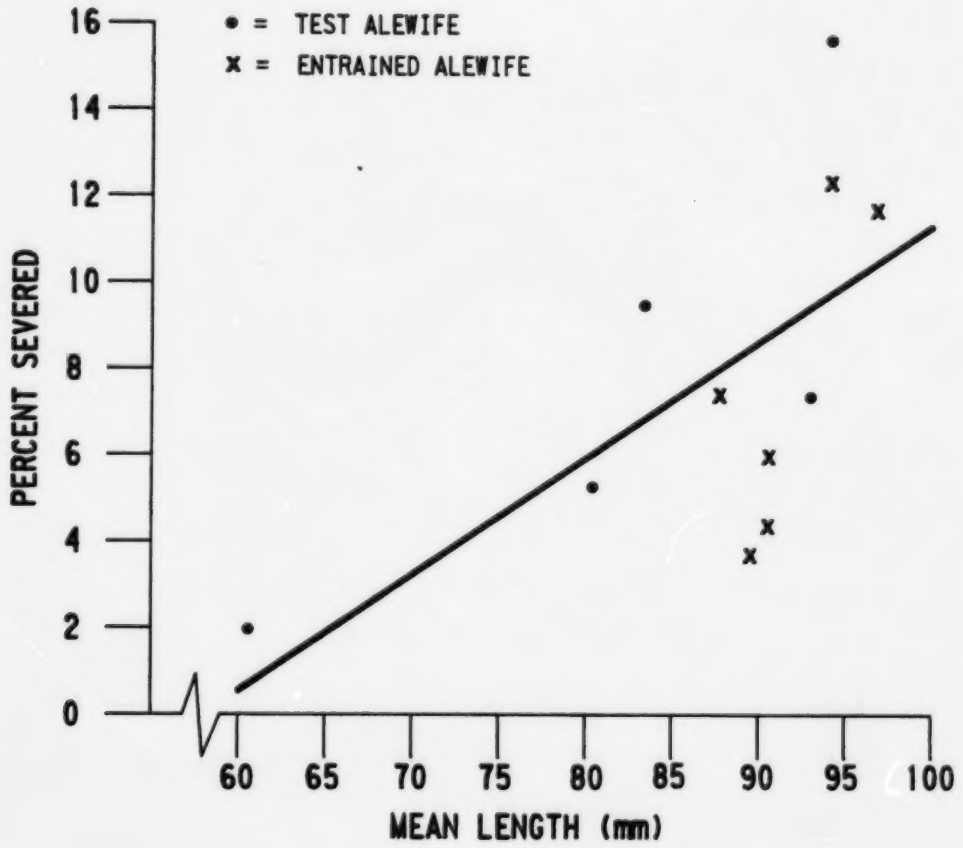


FIG. 12. Relationship of severed test and entrained alewife to mean length of recaptured dead.

MORTALITY OF YELLOW PERCH

Ten estimates of yellow perch mortality are available. The estimates of turbine induced mortality are derived in the same manner as those calculated for entrained alewife. The perch originated in the Fourth Lake reservoir and were entrained in the turbine flow and subsequently captured in the fish recapture gear.

The average turbine induced mortality of these entrained yellow perch was 13.6% (Table 5).

Some of the perch were held in live boxes in the headpond for subsequent release as test and control fish. One test was undertaken with these fish near the end of the test period. The corrected turbine mortality for this test using re-released perch was 12.6%. An earlier test using immersion staining techniques resulted in 100% mortality of test fish and the results of this test are not included in any further analysis, although we refer to this test in the discussion section. Both these tests are summarized in Table 6.

COMPARISON OF TROUT, ALEWIFE AND PERCH MORTALITY

Von Raben (1957) presents a formula for calculating the probability that a fish will be injured by contact with a turbine runner blade. His formula incorporates a correction factor to account for the fact that all theoretical contacts will not lead to recognizable injury. The correction factor was derived from empirical data of eel passage through a Kaplan turbine and adjusted the theoretical results with observed injuries to eels. The formula calculates the average velocity of flow as it approaches the runner blades and the distance the water and fish would move between the leading blade edges during normal rotational speed of the runner. The probability of a fish passing the runner blades without being hit is a direct function of fish length. Von Raben's formula for a propeller turbine is as follows:

$$P = 1 \times \frac{\cos \alpha . b . c . \quad (e^2 - f^2)}{240d} \times g$$

where:

P = probability of injury through contact with runner blade in percent.
1 = length of fish in cm.
α = angle of inlet flow to runner (incidence angle).
b = number of runner blades.
c = RPM of the runner.
d = average discharge in m^3/s.
e = runner diameter in m.
f = hub diameter in m.
g = correction factor (0.43).

In most cases in the past, use of the Von Raben formula has considerably over-estimated turbine mortality in comparison with that observed (Bell 1981, Ruggles and Collins 1981).

Table 7 compares the mean length, the percent severed, the percent injured and "uninjured" dead, the probability of injury and the estimate of mean turbine induced mortality for trout, alewife and perch. All the

TABLE 5

Mortality estimates of entrained Yellow perch.

OBSERVATION	DATE	WATER TEMP. (°C)	GATE[1] (%)	NUMBER SEVERED	WHOLE DEAD	TOTAL DEAD	NUMBER LIVE	MEAN[2] LENGTH (mm)	TOTAL CAPTURE	ESTIMATED[3] MORT. (%)
1	23/09/87	14.5	80	3	9	12	36	--	48	25.0
2	14/10/87	11.0	80	3	7	10	36	--	46	21.7
3	22/10/87	10.0	80	5	3	8	68	--	76	10.5
4	26/10/87	9.0	80	3	4	7	45	--	52	13.5
5	27/10/87	9.5	80	14	3	17	86	101.5	103	16.5
6	27/10/87	9.5	80	6	4	10	104	101.5	114	8.8
7	29/10/87	9.5	80	3	3	6	68	102.0	74	8.1
8	29/10/87	9.5	80	2	6	8	77	102.3	85	9.4
9	30/10/87	9.5	80	2	5	7	27	111.2	34	20.6
10	30/10/87	9.5	80	1	1	2	95	116.2	97	2.1
	Mean estimated mortality									13.6

1. Normal Turbine Operating Gate (80%)
2. Mean Length Of Captured Live Fish
3. Estimated % Mort. = (Total Dead / Total Capture) x 100

TABLE 6

Tests conducted with introduced Yellow perch.

TEST	DATE	WATER TEMP. (°C)	GATE (%)	[1] TYPE	NUMBER RELEASED	MEAN [2] LENGTH (mm)	NUMBER SEVERED	WHOLE DEAD [3] INJURED	WHOLE DEAD [3] UNINJURED	TOTAL DEAD	NUMBER LIVE	MORT [4] (%)	EST. [5] MORT. % [6]
1	27/08/87	19.5	67	T	56	--	1	1	31	33	--	100.0	100.0
				C	65	--	0	0	30	30	2	93.8	
27	27/10/87	9.5	80	T	397	112.6	16	8	33	57	221	20.5	12.6
				C	175	114.3	0	1	10	11	111	9.0	

1. T = Test
   C = Control

2. Mean length of released fish.

3. Injured = Whole Dead Fish With Visible Injury
   Uninjured = Whole Dead Fish With No Visible Injury

4. % Mort. = (Total Dead / Total Recapture) x 100

5. Mortality from turbine effects.

TABLE 7

Summary of trout, alewife and perch mortality in the Fourth Lake turbine (s = standard deviation).

Species and/or Sub Groups	Trout [1]	Alewife [2]	Alewife [3]	Perch [4]	Perch [3]
Number of Tests or Observations	20	5	10	1	10
Mean Length in mm	114 s = 16	84 s = 14	91 s = 3.1	113	105 s = 5.7
Severed (%)	5.5 s = 2.5	7.9 s = 5.2	7.9 2 = 3.3	4.0	5.8 s = 3.3
"Uninjured" Dead (%)	11.3 s = 8.1	34.0 s = 19	----	2.0	----
Injured Dead [5] (%)	8.0 s = 2.8	31.7 s = 19	---	10.0	----
Probability of Injury [6]	17.5	12.9	14.0	17.4	16.2
Mortality Estimate (%)	24.7 s = 11	66.5 s = 12	14.0 s = 3.6	12.6	13.6 s = 7.2

1. Test trout excluding tests where the water temperature exceeded 14°C.
2. Alewife that were captured and transported from the Tusket River marked and released into the penstock along with controls.
3. Alewife and yellow perch that left the headpond via the turbine route on their own volition.
4. Perch that were captured after passing through the turbine, held for a number of days in a live box in the headpond, marked and released into the penstock along with controls.
5. Includes severed and all dead fish with visible injuries.
6. See explanation in text.

percent estimates are calculated from the total number of fish exposed to turbine injury rather than a percent of dead fish. Thus, they represent probabilities that a fish passing through the turbine would be severed, killed with no visible injury, or killed with a visible injury including severing.

Estimates for alewife and perch are subdivided into two groups corresponding to fish that were experimentally released through the turbine by way of the penstock and those that were entrained by the turbine flow while migrating out of the reservoir. The latter were not handled prior to their capture in the fish recapture gear, while the former were accompanied by control releases to correct for fish handling and recapture losses not directly attributable to turbine passage.

Size differences were not great between the species or between the sub-groups of test and entrained fish that passed through the turbine. The probability of a fish being severed appears to be slightly greater for alewife even though alewife were slightly shorter than trout and perch. Uninjured dead were common in trout and alewife tests involving released experimental fish. Dead fish that appear in this classification probably reflect mortality other than that directly caused by turbine inflicted injuries. No estimate of injury type is available for the entrained alewife and perch. The low overall mortality estimates for these naturally migrating fish, coupled with the relatively high proportion of severed fish, reduces the probability that many fish could be classified as "uninjured" dead. The probability of alewife being severed was the same for the transported experimental fish and the fish that were entrained by the turbine flow.

The probability of injury calculated from Von Raben's formula provides a useful reference point to compare the overall mortality estimates and the proportions of severed, uninjured and injured dead fish. Unlike other reported use of this formula, in the present application the probability of injury is below the estimate derived from experimental results at the Fourth Lake tube turbine for experimental releases of trout and alewife. In the case of entrained alewife and perch, the formula derived estimate was 100% and 116% of that estimated by direct observation, respectively. Turbine mortality estimates for trout and perch included delayed mortality of one week, while alewife mortality reflects the immediate mortality after turbine passage.

The most striking observation from Table 7 is the difference in the mortality estimates for alewife derived from tests of alewife from the Tusket River and estimates derived from entrained alewife that had left the headpond via the turbine route on their own volition. This difference is examined more closely in the following section.

DISCUSSION

TROUT MORTALITY

The lack of correlation between fish length and gate opening with trout mortality was unexpected since previous work had demonstrated both variables to be important in Francis units (Cramer and Olgher 1961, Ruggles and Collins 1981, and Wunderlich and Dilley 1985). In Francis turbines the wicket gates not only control the flow but also impart a whirling motion to the water entering the area between the vanes. In addition, fish passing through the wicket gates of a Francis machine are introduced close to the leading edges of the turbine buckets. If clearances between the trailing ends of the gates and the leading edges of the buckets is critical, especially with larger fish and higher peripheral runner speeds, then gate opening and fish length would be expected to be important parameters influencing fish passage mortality in Francis machines. The high variability in the Fourth Lake test results may have masked the effects of fish length and gate opening, although it appears that these variables have a different impact on fish mortality in a tube turbine than in a Francis turbine.

The influence of water temperature on turbine induced mortality was also unexpected. It is the first time that an environmental factor has been proven to significantly affect turbine induced fish mortality. Temperature probably only affects the "uninjured" dead component of the observed mortality. The "uninjured" dead component, however, accounted for 46% of the total trout mortality estimate; hence environmental factors, extraneous to turbine and fish characteristics, may have had an important influence on turbine mortality estimates at Fourth Lake.

Some observers have speculated that environmental conditions might influence results of turbine testing, however, the use of control fish should correct for extraneous environmental conditions beyond the control of the researcher. The theory of experimental controls is that they correct for all the uncontrollable variables involved in the experimental design. Thus, the strict use of controls allows for the valid measurement of the test parameter under investigation. In the case of Fourth Lake tests, control fish were as similar to test fish as could be accomplished. They experienced the exact handling, marking, release and recapture procedures as the test fish. The only difference between test and control fish was exposure to turbine passage, therefore, the difference between test and control fish mortality should be a valid measure of turbine induced mortality.

One explanation for the unexpected impact of temperature on trout mortality may relate to the combined stress of turbine passage and recapture by the fish recapture gear. Fish that survive turbine passage, but are under a temperature stress, may die when subjected to the additional stress of recapture. Control fish, on the other hand,

have not been stressed by turbine passage. Thus, capture and temperature stress alone are not sufficient to cause mortality in the controls.

The influence of fish length and gate setting on the proportion of "uninjured" dead test and control trout indicates that a proportion of these fish were killed in the recapture gear. High flows accompanying higher gate settings result in high velocities and greater turbulence in the fish recapture gear than at lower gate settings. These conditions are conducive to higher fish mortality. Larger fish can handle this increase in velocity and turbulence more effectively than smaller fish. Ruggles and Collins (1981) found that larger trout were not injured to the same degree as smaller trout in similar fish recapture gear. They also found that injuries to control trout were directly related to turbine gate setting.

The influence of fish length on the probability of a fish being severed is not surprising, even though fish length was not found to influence overall mortality. Ruggles and Collins (1981) found a similar relationship between fish length and percent of recaptured trout that were severed at the Lequille Francis turbine. They found that the proportion of fish severed showed a linear relationship with fish length after the effect of gate opening was removed. Both gate and fish length were significant ($P<.01$) in influencing the proportion of severed fish in the Lequille tests. Trout size was similar at Lequille and Fourth Lake. The proportion of severed fish to the overall mortality estimate at Lequille and Fourth Lake were also similar, 25% and 23%, respectively. Wicket gate opening did not influence the proportion of fish severed at Fourth Lake.

It is interesting to compare the overall trout mortality estimate at Fourth Lake with results from other turbine fish passage research. A summary of fish mortality estimates derived from research at Francis, vertical Kaplan, and Tube turbines is presented in Table 8. The only other research at a tube turbine is at the Annapolis tidal powered unit on the Annapolis River, Nova Scotia. The fish mortality estimates involve both juvenile and adult alosid species (alewife and shad) and may be high compared to similar results derived from juvenile salmonid species. The mortality estimates for Francis and vertical Kaplan units are based on research with juvenile salmon and trout.

The average trout mortality of 25% for the Fourth Lake turbine appears high compared to other Kaplan turbines. Most reviewers of turbine test data have noted that Francis units usually inflict higher mortality to fish than vertical Kaplan types. In studies that have compared vertical Kaplan and Francis machines under similar conditions, however, fish mortality was the same. For instance, Cramer and Oligher (1961) experimented with model Francis and Kaplan 30 cm runners under similarly varying runner speeds, heads and runner elevations relative to

TABLE 8

Summary of turbine mortality estimates for Francis, Kaplan and Tube turbines.

FRANCIS UNITS[1]

Head Plant	Head m	RPM	Peripheral Velocity m/s	Runner Diameter m	Runner Elevation Above Tailwater m	Average Percent Estimated Mortality
Baker	76	300	24	1.5	-1.5	31
Cushman	137	300	33	2.1	3.4	41
Elwha	32	300	18	1.5	4.3	10
Faraday	37	360	19	1.0	4.0	4
Glines	59	225	26	2.3	2.1	36
Leaburg	27	225	27	2.3	3.6	17
Lequille	118	519	37	1.41	2.0	48
North Fork	41	139	25	2.95	1.5	26
Publishers	13	300	14	0.91	7.1	13
Puntledge	104	277	31	2.2	0.6	33
Ruskin	38	120	24	3.8	3.0	10
Seton Ck.	43	120	29	3.7	4.9	9
Shasta	125	138	34	4.0	0.9	39
Sullivan	13	240	20	1.9	7.0	20
Mean Mortality						24

VERTICAL KAPLAN UNITS[1]

Big Cliff	27	163	16	3.7		14
Bonneville	18	75		7.0		9
Foster	31	257	34	2.5	2.1	8
Gold Hill	6					8
Hadley Falls	16	129		4.3		18
Model UBC	16	2800	36	0.24	2.1	38
Sullivan	13	240			5.8	10
Tobique	23			2.7	-5.2	18
Tusket	6			1.8	0	19
Walterville	17			3.8	0	9
Wells	20					16
Rock Island	12	86	31	7	-9.8	5
Mean Mortality						14

TUBE UNITS

Fourth Lake	23	360	32	1.65	-1.1	25
Annapolis	5.5	50	20	7.6	—	40

[1] Source: Eicher Associates 1987.

tailwater, and found test fish mortality was essentially the same for both models. The conclusion is that although Francis units do tend toward causing greater fish mortality, this is due to site characteristics rather than turbine design.

Eicher Associates (1987) show a strong correlation between runner peripheral velocity and fish mortality in Francis turbines. They conclude that it is the principal variable affecting fish mortality in this turbine type. No similar effect was found with vertical Kaplan units. In a Francis turbine, fish are more likely to be struck by the periphery of the runner because this is where they enter the unit. The wicket gates introduce them directly into the spaces between the peripheral edges of the runner blades. In vertical Kaplan units, because downstream migrants tend to move downstream through the upper level of the intake passageway, they are believed to enter the turbine casing near the runner hub and contact the runner in that area (Long 1968).

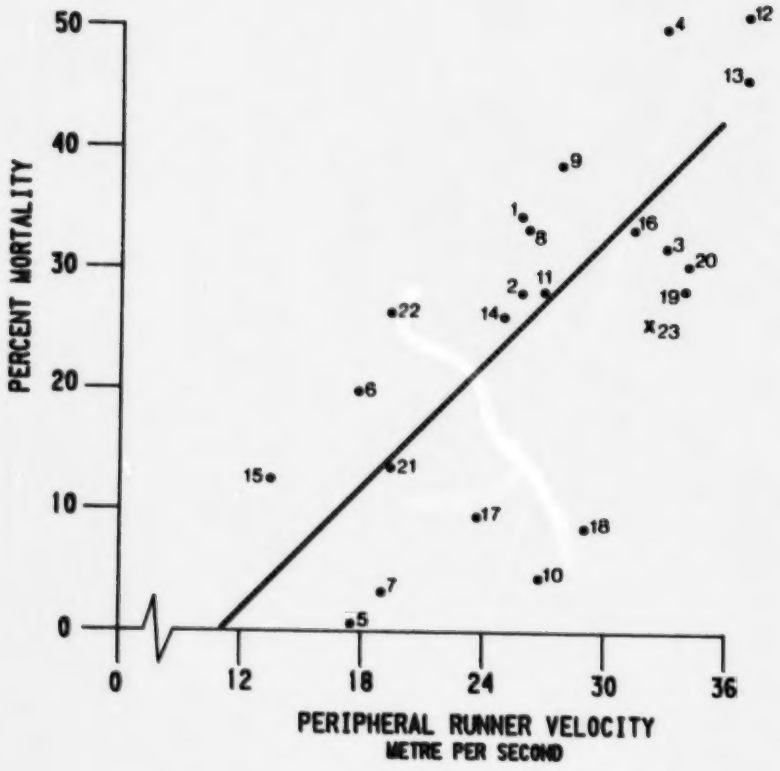
In tube type machines such as the Fourth Lake S-turbine, peripheral velocity may be an important factor since fish may be moving through the penstock near the roof in an effort to compensate for increasing hydrostatic pressure and hence approach the runner near its periphery. Figure 13 reproduces the relationship of peripheral runner velocity and salmonid fish mortality in Francis units found by Eicher Associates (1987). Also plotted is the Fourth Lake trout mortality estimate. The Fourth Lake estimate of turbine mortality falls below the regression line for Francis units.

Based on a comparision with other fish mortality estimates, including those derived from Francis machines, the trout mortality estimate of 25% appears to be a reasonable estimate of trout mortality at Fourth Lake. The high proportion of "uninjured" dead and the effect of water temperature presents some uncertainty as to the extent to which turbine related injury is wholly responsible for this mortality estimate.

Because of this caveat, the mortality estimate for trout is reduced in a latter section of this report.

ALEWIFE MORTALITY

Table 9 is a summary of results of turbine passage tests conducted with juvenile alewife, along with some design parameters of each of the four hydro sites where the research was undertaken. These results were conducted under a variety of field conditions but incorporated accepted experimental design.The data summarized for Fourth Lake involved fish transported from the Tusket River, held for one or two days in holding pens in the Fourth Lake reservoir, and then released under experimental test conditions into the turbine penstock (test fish) and into the exit



NUMBER KEY

1.	BAKER	-- SOCKEYE
2.	BAKER	-- COHO
3.	CUSHMAN	-- 1960
4.	CUSHMAN	-- 1961
5.	ELWHA	-- 1954
6.	ELWHA	-- 1983
7.	FARADAY	
8.	GLINES	-- 1954
9.	GLINES	-- 1983
10.	LEABURG	-- 1958
11.	LEABURG	-- 1983
12.	LEQUILLE	-- 1980
13.	LEQUILLE	-- 1981
14.	NORTH FORK	
15.	PUBLISHERS	
16.	PUNTLEDGE	
17.	RUSKIN	
18.	SETON CREEK	
19.	SHASTA	-- JANUARY
20.	SHASTA	-- NOVEMBER
21.	SULLIVAN	-- CHINOOK
22.	SULLIVAN	-- STEELHEAD
23.	FOURTH LAKE S-TURBINE X	

FIG. 13. Relationship of peripheral runner velocity to salmonid mortality in Francis turbines. Redrawn from Eicher Associates (1987). The Fourth Lake tube turbine data is shown by an X and is numbered 23.

TABLE 9

Alewife turbine passage mortality at four hydro installations along with selected design parameters for each site.

	Hadley Falls	Tusket	Annapolis	Fourth Lake
1. Type of Turbine	Kaplan	Kaplan	Straflo	Tube
2. Rated Head	15.5 m	8 m	5.5 m	23 m
3. Rated Speed	129 RPM	225 RPM	50 RPM	360 RPM
4. No. of Runner Blades	5	4	4	6
5. Runner Diameter	4.3 m	1.8 m	7.6 m	1.7 m
6. Discharge	118 m^3/s	14 m^3/s	408 m^3/s	15 m^3/s
7. Angle of Inlet Flow to Runner	--	--	26°	25°
8. Rated Output	17 MW	0.7 MW	17.8 MW	3.1 MW
9. Fish size	90 mm	85 mm	90 mm	90 mm
10. Average Mortality	63-83%	53%	54%	66%

of the draft tube (control fish). All of the mortality estimates are high (compared to similar estimates for juvenile salmon and trout) and surprisingly similar, considering the wide range of turbine parameters reported. To date, high alewife mortality has been explained on the basis of a general lack of robustness or to a specific vulnerability to pressure change (Gloss et al. 1982, Kynard et al. 1982, Stokesbury 1986).

On the basis of a comparision of the reported alewife mortality estimates, the results of testing with the transported alewife from the Tusket River appear to be consistent with what is generally believed to characterize alewife mortality in hydraulic turbines. However, mortality estimates derived from naturally migrating alewife that had become entrained by the Fourth Lake turbine flow, indicate a much lower level of turbine induced mortality ie. 14% vs 66%. These fish entered the penstock from the headpond in a natural manner, passed through the turbine and were captured in the fish recapture net immediately below the exit of the draft tube. Unfortunately, injury type was not recorded for these entrained alewife except to note the number of severed individuals. It is interesting to note, however, that the degree of severing in both the transported Tusket River alewife and in the entrained alewife was the same. We conclude that the mortality estimate derived from the entrained alewife more accurately reflects the true extent of turbine induced mortality at Fourth Lake, than does the estimate derived from the transported alewife.

Once again, the careful use of control fish does not appear to have isolated turbine effects from other parameters affecting alewife mortality derived from the transported fish. The large number of uninjured dead, representing 51% of the total alewife mortality, may account for some of the discrepancy between the two mortality estimates. However, even subtracting all of the"uninjured" dead from the total alewife test mortality estimate, the adjusted mortality estimate is over twice that calculated for the entrained alewife.

The condition of experimental fish used in turbine tests will influence the survival of both test and control fish. It is not clear, however, exactly how this factor impacts turbine fish passage results. If control fish mortality is used to correct the overall mortality obtained from fish passage tests, it should be theoretically possible to isolate the mortality due to turbine passage from those relating to the poor condition of the fish.

The explanation for why control mortality is not correcting for that portion of fish mortality not directly attributable to turbine effects, may be similar to that proposed earlier for temperature effects. Thus fish that survive turbine passage are in such poor condition that they are unable to survive the additional stress inflicted by the fish recapture gear. Control fish in poor condition,

on the other hand, only have to contend with the stress of recapture. Clearly, the results obtained at Fourth Lake suggest that previous estimates of alewife mortality during turbine passage may have been greatly overestimated.

Whatever the explanation, the direct observation of alewife mortality at the Fourth Lake tube turbine raises doubts about previous estimates of fish mortality in turbines. In the case of alewife and probably other alosid species, previous turbine related mortality estimates are almost certainly too high.

PERCH MORTALITY

Perch mortality due to turbine passage at Fourth Lake appears to be in the 12% to 14% range. Only one valid test using introduced fish is available to compare with the ten mortality estimates derived from observations of entrained perch. Both perch mortality estimates are similar. One perch test using immersion staining techniques resulted in 100% mortality of test fish, again pointing out the importance of the condition of test and control fish in deriving mortality estimates.

COMPARISION OF TROUT, ALEWIFE AND PERCH MORTALITY

Experiments at Fourth Lake allow comparision of turbine fish passage mortality in three important and diverse fish families: Clupeidae, Salmonidae and Percidae.

The Clupeids are herring-like fish which are primarily ocean schooling species. They are pelagic zooplankton feeders, have thin walled swim bladders, and are sometimes characterized by rapid, catastrophic mortalities. These large die-offs have been associated with fluctuating water temperature. Hoar (1952) suggested an "exhausted thyroid" as the trigger mechanism for these mortalities. Clupeids are physoclistic, meaning they do not possess a duct between the swim bladder and esophagus and are less adapted to adjust to rapid pressure change than fish possessing such a duct. In addition, Blaxter and Hoss (1979) provide evidence that the auditory bulla system in Clupeids is vulnerable to pressure damage. Juvenile Clupeids are noted to be extremely susceptible to handling and transportation stress.

The Salmonidae have been the subject of more turbine fish passage research than any other family of fishes. Tests have shown salmonids to be very durable and capable of surviving a variety of handling, marking and transportation procedures. Salmonids are physostomous (possess a duct from the swim bladder to the esophagus) and are better adapted to accommodate pressure changes than physoclistic fishes such as the Clupeids and Percids.

The Percidae are members of the spiny-rayed fishes of the order Perciformes. The family includes the valuable walleye (Stizostedion vitreum), the most economically valuable species in Canada's inland waters (Scott and Crossman 1973). The percids do not have a pneumatic duct from the swim bladder to the esophagus.

A review of the literature suggests that species of fish vary greatly in their susceptibility to injury during turbine passage. The Swedish researcher, Monten was one of the earliest to compare fish passage success among different species. He states (Monten 1955) that adult eels, "despite their considerable length, get through in better shape than fish of the pollack or bream families, ie. fish with large scales". Perch about 12 cm long showed 35% greater turbine losses than Atlantic salmon of the same length. Monten attributes this difference to the increased flexibility and smoothness of salmon that allows them to pass the edge of the turbine blade more readily and thus avoid being broken up.

Kynard et al. (1982) conducting tests in a Kaplan turbine, found that Atlantic salmon smolt mortality was much less than juvenile clupeids (10% vs. 70%). Gloss et al. (1982) found mortalities of Atlantic salmon and steelhead trout in an Ossberger turbine to be about 50%, while striped bass and shad suffered almost 100% mortality.

In general, salmon and trout species have been reported to suffer lower mortality than perch and alewife during turbine passage. The results at Fourth Lake do not confirm this general observation. In fact estimated mortality to entrained perch and alewife was about one half that estimated for trout. It may be that the species difference in susceptibility to injury during turbine passage is more a reflection of the species reaction to stresses associated with the experimental design rather than to the stresses associated with turbine passage. Another explanation may be that the trout mortality at Fourth Lake was over estimated, or conversely, that alewife and perch mortalities were underestimated. We conclude, however, that alosids are not more vulnerable to turbine passage than salmonids.

COMPARISION OF ALEWIFE MORTALITY ESTIMATES AT FOURTH LAKE AND ANNAPOLIS

Table 10 compares estimates of turbine induced mortality of juvenile alewife at Fourth Lake and Annapolis tube turbines. Estimates derived from both test and entrained alewife at Fourth Lake are tabulated, as are estimates based on Von Raben's formula. Test fish estimates at Annapolis involved comparison of control and test mortalities in fish recapture nets set above and below the turbine. The estimate did not include mortality of fish having no discernible physical damage, ie. "uninjured" dead. Unfortunately, it was difficult to separate injuries caused by the recapture gear (ichthyoplankton nets) from those caused by the turbine. The fish in both the control

net and the test net were naturally migrating fish occurring above and below the Annapolis turbine.

TABLE 10

Comparison of juvenile alewife mortality estimates at Fourth Lake and Annapolis tube turbines.

	Annapolis	Fourth Lake
1. Test Fish Estimates	54%	66%
2. Entrained Fish Estimates	--	14%
3. Von Raben Estimate (using 9 cm as the mean fish length)	1.2%	14%
4. Peripheral Runner Velocity Estimate	2.5%	12.5%

On the basis of the relative size, speed and head characteristics of the two sites, one would expect the mortality of similar fish passing through the turbines to be much lower at Annapolis than at Fourth Lake. The fact that the Von Raben formula provides a mortality estimate that is in agreement with the observed mortality of entrained alewife at Fourth Lake, provides some justification for the use of Von Raben's formula for estimating alewife mortality at Annapolis. On this basis, an alewife mortality of 1.2% during passage through the Annapolis STRAFLO turbine is derived. The Von Raben formula would over-estimate mortality at Annapolis compared to Fourth Lake if head and resultant pressure related injuries were important in determining alewife mortality, since head is not accounted for in the fish mortality formula and the head at Fourth Lake greatly exceeds that at Annapolis.

Another method of estimating fish mortality at Annapolis is to use the relationship of peripheral runner velocity to fish mortality shown in Figure 13. It should be noted that this relationship is for salmon and trout and not alewife. If we assume that fish mortality in the STRAFLO turbine lies below the regression line for Francis turbines to a similar degree as was shown for the Fourth Lake S-Turbine, then the mortality of juvenile salmonids at Annapolis would be about 5%. Since Fourth Lake alewife mortality was about one-half that estimated for trout, juvenile alewife mortality estimate of about 2.5% can be derived on the basis of the peripheral runner velocity of the STRAFLO turbine

and trout and alewife mortality estimates at Fourth Lake. The relative effect of peripheral velocity may be less at Annapolis if fish are not migrating near the runner periphery as is expected to be the case at Fourth Lake.

It seems apparent that the original estimate of juvenile alewife mortality of 54% at the Annapolis tidal powered station is too high. On the basis of experience at Fourth Lake and present knowledge of fish passage through turbines, a preliminary estimate of 1 to 2.5% mortality of juvenile alewife is suggested as a more reasonable level of impact at the Annapolis STRAFLO turbine.

A BEST ESTIMATE FOR TROUT MORTALITY

Fish mortality in turbines is probably the result of a complex set of factors, only a few of which are directly accounted for in the Von Raben formula. However, in the case of the Fourth Lake tube turbine, the formula derived mortality estimate agrees with observed mortality estimates of entrained alewife and provided mortality estimates similar to those calculated for yellow perch. Because of the high proportion of "uninjured" dead and the observed effects of water temperature on trout mortality at Fourth Lake, trout mortality derived from the Von Raben formula (17.5%) may be a more accurate estimate of turbine induced mortality than the estimate of 24.7% derived from the actual field tests.

CONCLUSIONS

Fish passage research at the Fourth Lake S-turbine using juvenile trout, alewife and yellow perch provide the following conclusions:

1. Fish mortality in this tube turbine is estimated to be:

   18% - 25% for trout
   14% for alewife
   14% for yellow perch

2. Among variables tested in 1987, water temperature was the most significant in influencing fish mortality during passage through the Fourth Lake turbine.

3. Fish length directly affected the chances of a fish being severed during passage through the turbine.

4. Peripheral runner velocity may be an important turbine parameter affecting fish mortality in tube turbines as well as in Francis types.

5. Alewife were not more susceptible than trout to mortality during passage through the Fourth Lake turbine.

6. Wicket gate setting did not influence turbine related fish mortality at Fourth Lake.

7. Previous estimates of juvenile alewife mortality due to turbine passage at the Annapolis tidal power station are believed to be too high.

8. The use of control fish releases did not correct for the impact of water temperature and fish condition on the success of fish passage through the Fourth Lake turbine.

9. The manner in which fish mortality estimates were derived had a profound impact on the results of fish passage research at Fourth Lake.

10. A careful inquiry into the methods of estimating fish passage mortality in hydraulic turbines is warranted in light of the findings at Fourth Lake.

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APPENDIX A

Summary of regression equations.
Regression statistics given only for regressions with $P \leq 0.1$.

Group	Dependent Variable	Independent Variable	P	N	Slope	Standard Error of Slope	y-Intercept	r^2
Transported Alewife	Control Mortality	Gate Setting	.550	5				
"	"	Water Temperature	.406	5				
"	"	Length of Dead Recapture	.245	5				
"	"	Length of Live Recapture	.289	5				
"	Corrected Mortality	Gate Setting	.254	4				
"	"	Water Temperature	.150	5				
"	"	Length of Dead Recapture	.121	5				
"	"	Length of Live Recapture	.434	5				
"	Uninjured	Gate Setting	.260	5				
"	"	Length of Dead Recapture	.102	5				
"	"	Length of Live Recapture	.246	5				
"	Injured	Gate Setting	.906	5				
"	"	Length of Dead Recapture	.461	5				
"	"	Length of Live Recapture	.351	5				
"	Severed	Gate Setting	.605	5				
"	"	Length of Dead Recapture	.059	5	.006	.002	-.232	.746
"	"	Length of Live Recapture	.345	5				
Entrained Alewife	Mortality	Water Temperature	.756	10				
"	"	Length of Dead Recapture	.355	10				
"	Severed	Length of Live Recapture	.094	10	.016	.007	-1.20	.544
Entrained Yellow Perch	Mortality	Water Temperature	.122	10				
"	"	Length of Live Recapture	.848	10				
"	Severed	Length of Live Recapture	.465	10				
All Trout	Recapture of Released Dead Control	Gate Setting	.004	8	.852	.120	15.90	.722
"	"	Length of Released	.652	8				
"	Control Mortality	Water Temperature	.024	25	.016	.007	-.047	.201
"	"	Length of Released	.014	25	-.003	9.9×10^{-4}	.443	.235
"	"	Gate Setting	.022	25	.002	9.7×10^{-4}	-.003	.208
"	"	$(\text{Gate Setting})^2$	.056	25	1.5×10^{-5}	7.6×10^{-6}	.083	.149

Group	Dependent Variable	Independent Variable	P	N	Slope	Standard Error of Slope	y-Intercept	r^2
All Trout	Corrected Mortality	Water Temperature	.032	25	.034	.015	.151	.184
"	"	Length of Released	.275	25				
"	"	Gate Setting	.919	25				
"		$(\text{Gate Setting})^2$	.977	25				
"	Uninjured	Water Temperature	.001	25	.045	.135	-.184	.443
"	"	Length of Released	.004	25	-.005	.002	.952	.301
"	"	Gate Setting	.027	25	.004	.002	.091	.196
"	Injured	Water Temperature	.073	25	.010	.005	.029	.133
"	"	Length of Released	.190	25				
"	"	Gate Setting	.070	25	.001	.001	.058	.135
"	Severed (gate=100)	Length of Released	.001	2	-.001	--	.385	1.00
"	Severed (gate=80)	"	.026	8	.006	.002	.388	.587
"	Severed (gate=67)	"	.066	9	.001	.001	.133	.403
"	Severed (gate=40)	"	.117	6	.008	.004	-.763	.497
"	Severed	Gate Setting	.999	25				
"	"	Length of Released	.015	25	.002	.001	-.036	.230
"		Water Temperature	.671	25				
	Corrected Mortality (gate=100)	Length of Released	.001	2	-.003	--	.889	1.00
"	Corrected Mortality (gate=80)	Length of Released	.419	8				
"		Water Temperature	.001	8	.498	.090	-6.365	.837
"	Corrected Mortality (gate=67)	Length of Released	.802	9				
"	"	Water Temperature	.133	9				
"	Corrected Mortality (gate=40)	Length of Released	.344	6				
"	"	Water Temperature	.502	6				
(temp<14°C)	Control Mortality	Water Temperature	.003	20	.033	.010	-.226	.392
"	"	Length of Released	.002	20	-.004	.001	.617	.413
"		Gate Setting	.024	20	.003	.001	-.014	.254
"	Corrected Mortality	Water Temperature	.730	20				
"	"	Length of Released	.280	20				
"	"	Gate Setting	.599	20				

Group	Dependent Variable	Independent Variable	P	N	Slope	Standard Error of Slope	y-Intercept	r^2
Large Trout	Control Mortality	Water Temperature	.177	10				
"	"	Length of Released	.504	10				
"	"	Gate Setting	.330	10				
"	Corrected Mortality	Water Temperature	.275	9				
"	"	Length of Released	.316	9				
"	"	Gate Setting	.146	9				
"	Uninjured	Gate Setting	.270	10				
"	"	Length of Released	.083	10	-.006	.003	1.06	.328
"	Injured	Gate Setting	.119	10				
"	"	Length of Released	.192	10				
"	Severed	Gate Setting	.525	10				
"	"	Length of Released	.058	10	.001	7.2×10^{-4}	.052	.378
(temp<14°C)	Control Mortality	Water Temperature	.089	9	.027	.014	-.175	.357
"	"	Length of Released	.272	9				
"	"	Gate Setting	.300	9				
"	Corrected Mortality	Water Temperature	.275	9				
"	"	Length of Released	.316	9				
"	"	Gate Setting	.146	9				
"	Severed	Gate Setting	.716	9				
"	"	Length of Released	.322	9				
"	Injured	Gate Setting	.171	9				
"	"	Length of Released	.354	9				
"	Uninjured	Gate Setting	.299	9				
"	"	Length of Released	.558	9				
Small Trout	Control Mortality	Gate Setting	.372	10				
"	"	Length of Released	.154	10				
"	"	Water Temperature	.207	10				
"	Corrected Mortality	Gate Setting	.801	9				
"	"	Length of Released	.624	9				
"	"	Water Temperature	.782	9				
"	Severed	Gate Setting	.413	10				
"	"	Length of Released	.293	10				
"	Injured	Gate Setting	.483	10				
"	"	Length of Released	.822	10				
"	Uninjured	Gate Setting	.159	10				
"	"	Length of Released	.056	10	-.007	.003	1.10	.384

Group	Dependent Variable	Independent Variable	P	N	Slope	Standard Error of Slope	y-Intercept	r^2
(Temp 14°C)	Control Mortality	Gate Setting	.348	9				
"	"	Length of Released	.039	9	-.005	.002	.757	.479
"		Water Temperature	.121	9				
"	Corrected Mortality	Gate Setting	.801	9				
"	"	Length of Released	.624	9				
"	"	Water Temperature	.782	9				
"	Severed	Gate Setting	.227	9				
"	"	Length of Released	.767	9				
"	Injured	Gate Setting	.592	9				
"	"	Length of Released	.367	9				
"	Uninjured	Gate Setting	.188	9				
"	"	Length of Released	.302	9				

APPENDIX B
Injury summary table.

TEST	SPECIES[1]	TYPE[2]	SIZE[3]	RUPTURED AIR BLADDER	POPPED EYE	MISSING EYE	CRUSHED HEAD	SKELETAL FRACTURE	LACER-ATION	EYE HEMORAGE	INTERNAL HEMORAGE	MUSHED ORGANS
2	A	T	N	5	0	2	0	0	2	2	6	0
2	A	C	N	0	0	0	0	2	1	2	2	0
10	A	T	N	11	5	2	2	0	1	10	38	0
10	A	C	N	0	1	0	0	0	0	5	8	0
11	A	T	N	2	2	2	1	1	3	3	13	0
11	A	C	N	0	0	0	1	0	2	3	8	0
14	A	T	N	5	1	3	1	0	5	3	20	1
14	A	C	N	0	1	1	2	0	2	0	9	0
17	A	T	N	1	1	2	1	1	1	4	6	1
17	A	C	N	0	0	0	0	0	0	2	2	0
1	P	T	N	0	0	0	0	0	1	0	0	0
1	P	C	N	0	0	0	0	0	0	0	0	0
27	P	T	N	3	0	0	0	3	4	0	1	0
27	P	C	N	0	0	0	0	0	0	1	0	0
5	T	T	N	0	1	2	0	1	1	0	0	2
5	T	C	N	0	0	0	0	0	0	0	0	0
6	T	T	N	1	0	0	0	1	2	0	3	2
6	T	C	N	0	0	0	0	0	0	0	0	0

TEST	SPECIES[1]	TYPE[2]	SIZE[3]	RUPTURED AIR BLADDER	POPPED EYE	MISSING EYE	CRUSHED HEAD	SKELETAL FRACTURE	LACER-ATION	EYE HEMORAGE	INTERNAL HEMORAGE	MUSHED ORGANS
7	T	T	N	1	0	0	0	0	0	1	0	0
7	T	C	N	0	0	0	0	0	0	0	0	0
9	T	T	S	4	0	0	0	0	0	1	1	0
9	T	C	S	0	0	0	0	0	0	0	0	0
9	T	T	L	3	0	0	0	1	0	1	0	0
9	T	C	L	0	0	0	0	0	0	0	0	0
12	T	T	S	2	0	0	0	0	0	1	0	0
12	T	C	S	0	0	0	0	0	0	0	0	0
12	T	T	L	1	0	0	0	0	0	0	2	0
12	T	C	L	0	0	0	0	0	1	0	1	0
13	T	T	S	1	0	1	0	1	0	1	3	0
13	T	C	S	0	0	0	0	0	0	0	0	0
13	T	T	L	0	0	0	0	1	1	0	1	0
13	T	C	L	0	0	0	0	1	0	0	0	0
14	T	T	S	0	0	0	0	2	0	1	0	0
14	T	C	S	0	0	0	0	0	0	0	0	0
14	T	T	L	1	2	1	0	0	0	0	1	0
14	T	C	L	0	0	0	0	0	0	0	0	0

TEST	SPECIES[1]	TYPE[2]	SIZE[3]	RUPTURED AIR BLADDER	POPPED EYE	MISSING EYE	CRUSHED HEAD	SKELETAL FRACTURE	LACER-ATION	EYE HEMORAGE	INTERNAL HEMORAGE	MUSHED ORGANS
15	T	T	S	0	0	0	0	0	0	0	0	0
15	T	C	S	0	0	0	0	0	0	0	0	0
15	T	T	L	0	0	2	0	0	0	0	0	0
15	T	C	L	0	0	0	0	0	0	0	0	0
16	T	T	S	0	0	0	0	0	0	0	0	0
16	T	C	S	0	0	0	0	0	0	0	0	0
16	T	T	L	0	1	0	0	1	1	0	0	1
16	T	C	L	0	0	0	0	0	0	0	0	0
18	T	T	S	0	1	1	1	1	1	1	2	0
18	T	C	S	0	0	0	0	0	0	0	0	0
18	T	T	L	1	0	0	0	0	1	0	0	0
18	T	C	L	0	0	0	1	0	0	0	0	0
19	T	T	S	1	0	0	0	0	3	0	1	0
19	T	C	S	0	0	0	0	0	0	0	0	0
19	T	T	L	1	1	0	0	0	2	1	0	0
19	T	C	L	0	0	0	1	0	0	0	0	0
23	T	T	S	0	0	1	0	1	1	1	0	0
23	T	C	S	0	0	0	0	0	0	0	0	0

TEST	SPECIES[1]	TYPE[2]	SIZE[3]	RUPTURED AIR BLADDER	POPPED EYE	MISSING EYE	CRUSHED HEAD	SKELETAL FRACTURE	LACER-ATION	EYE HEMORAGE	INTERNAL HEMORAGE	MUSHED ORGANS
23	T	T	L	0	0	0	0	0	2	0	0	1
23	T	C	L	0	0	0	0	0	0	0	0	0
24	T	T	S	0	0	1	1	0	0	0	0	0
24	T	C	S	0	0	0	0	0	0	0	0	0
24	T	T	L	0	0	0	0	0	0	0	0	0
24	T	C	L	0	0	0	0	0	0	0	0	0
25	T	T	N	0	0	0	0	0	0	1	0	0
25	T	C	N	0	0	0	0	0	0	0	0	0
26	T	T	N	0	0	0	0	0	0	1	0	0
26	T	C	N	0	0	0	0	0	0	0	0	0

1. A = ALEWIFE
   P = PERCH
   T = TROUT

2. T = TEST
   C = CONTROL

3. N = NO SIZE CLASSIFICATION
   L = LARGE SIZE CLASS
   S = SMALL SIZE CLASS